11. FIRE SAFETY ENGINEERING

11.1 FLAMMABLE FABRICS

The Flammable Fabrics Act (FFA) was passed in 1953 to protect individuals from serious burns due to wearing combustible apparel. The primary impetus for passage of the law was the increased incidence of burn injuries due to brushed rayon ("torch") sweaters. The FFA was based on a standard test, up to that time voluntary, which was derived substantially from research and testing at NBS. In late 1967 the Act was amended to extend and strengthen protection from the flammability hazards of other wearing apparel and interior furnishings such as carpets, drapes and furniture.

Responsibilities for implementing the Act were split among the Department of Health, Education & Welfare (HEW), for accident case investigation; the Federal Trade Commission, for enforcement of the law; and the Department of Commerce for development and promulgation of flammability standards. The Secretary of Commerce delegated the standards development responsibility to NBS. In 1968 NBS Director Allen Astin established a Task Force to begin implementation of the new responsibilities. An Office of Flammable Fabrics was established at NBS in 1969 under Elio Passaglia. In 1970 Joseph Clark was hired to direct the office.

Joseph Clark, director, Office of Flammable Fabrics

A computerized database was developed at NBS in 1970, from accident reports provided by HEW investigators. The accident data available indicated the most frequent and severe injuries and losses to be involved with children's sleepwear and certain interior furnishings in homes. Available accident data indicated that carpets and rugs, curtains and drapes, upholstered furniture, and beds were the items most frequently involved in residential fires. Sleepwear was the first item ignited more frequently than any other item in almost 2,000 fire incident reports available at the time. Laboratory work was accelerated to develop and evaluate test methods that were related to the situations documented in the accident case reports. The law required that standards be promulgated only to protect the public from "unreasonable risks" of the occurrence of fire leading to death, injury, or significant property damage. The standards must be "reasonable, appropriate and technologically practicable." The legal concept of unreasonable risk and the technical concepts underlying appropriate tests and flame-retardant technology framed an intense set of activities ranging from basic research through policy analysis. Scientists and attorneys in and out of government frequently found themselves in public debates, media appearances, and congressional testimony. A particularly troublesome issue involved the potential toxicity of the combustion products of some chemicals added to fibers and fabrics to increase their flame retardance.

Development of a test method for surface flammability of carpets and rugs proved relatively straightforward, so promulgation of this standard came about first, in 1970. All carpet and rugs 1.2 m x 1.8 m or larger were required to meet the requirements of standard FF1-70 (flammable fabrics). This requirement states that no more than one out of eight specimens shall burn a distance of 75 mm from the point of ignition when tested according to the prescribed method. The test method, known as the "pill test," involves subjecting a 290 mm x 290 mm specimen, which has been dried in an oven, to the flame from a standard igniting source in the form of a methenamine tablet. The tablet, or "pill," is placed on top of the pile in the center of the specimen and ignited with a match, providing a standardized flame source for a period of about 2 minutes. If the flame spread on the carpet is more than 75 mm from the point of ignition, the specimen fails; and if more than one specimen of eight fails, the style of carpet cannot be legally manufactured for sale. The burden of compliance with FF1-70 rests with the carpet manufacturer. Smaller carpets and rugs were subject to the same test, but since the risk from these items is smaller, it is required only that they be labeled as flammable. The standard for carpets and rugs smaller than 1.2 m x 1.8 m is designated FF2-70.

In 1971, the Secretary of Commerce proposed a flammability standard (FF3-71) for children's sleepwear in sizes 0 through 6X. The standard was issued to protect young children from death and serious burn injuries that had been associated with ignition of sleepwear garments, such as nightgowns and pajamas, by small open-flame sources. The test requires that vertically hung specimens of fabrics, seams, and trim of children's sleepwear garments must self-extinguish after three seconds exposure to a small open flame. Manufacturers of children's sleepwear must test prototypes of sleepwear garments with acceptable results before beginning production. Manufacturers must also sample and test garments from regular production. The standard does not require or prohibit the use of any particular type of fabric or garment design as long as the manufacturer successfully completes the prescribed prototype and production testing.

While work was proceeding on the children's sleepwear standard, investigation of interior furnishings continued to progress. The accident data indicated that smoldering cigarettes and other smoking materials provide the ignition source in most residential fires. Most victims in residential fires were asleep at the time of their injury. The data also indicate that a high percentage of the victims were partially incapacitated by alcohol, drugs, or infirmity associated with illness or old age. Smoldering cigarette ignition was the most frequent source of fires in bedding and upholstered furniture.

In 1972, the Secretary of Commerce issued a flammability standard (FF4-72) for mattresses and mattress pads to protect the public from death and serious burn injuries associated with ignition of mattresses and mattress pads by smoldering cigarettes. The standard prescribes a test for mattresses and mattress pads which requires placement of lighted cigarettes at specified locations on the surface of the mattress or mattress pad. An individual mattress or mattress pad prototype passes the test in the standard if no cigarette test location produces char length more than 50 mm in any direction.

In 1972, the Department of Commerce issued a notice regarding the need to develop a standard for upholstered furniture. This notice summarized the available accident data and solicited comments on the risks as well as the type of test method that would be appropriate. Assessing the ignition resistance of upholstered furniture is much more complex than mattresses due to the more complex geometry (both geometry of construction and geometry of exposure to a cigarette), more varied materials of construction, fabric coatings, backcoatings, liners, and the like.

In 1973, authority to issue flammability standards under provisions of the FFA was transferred from the Department of Commerce to the new Consumer Product Safety Commission (CPSC) by the Consumer Product Safety Act. Several key scientists transferred from NBS to CPSC to help provide continuity in the work on flammable fabrics.

In 1974, the Commission issued a flammability standard (FF5-74) for children's sleepwear in sizes 7 through 14. The safety requirements of the two children's sleepwear standards are nearly identical.

In 1976, CPSC contracted with the National Bureau of Standards to draft a standard for upholstered furniture's resistance to ignition from lit cigarettes, and a standard (PFF6-76) was proposed. By 1978, CPSC had made improvements to the proposed standard, and it was prepared for formal issuance. Industry opposition to the mandatory standard resulted in a compromise in which the mandatory standard was not promulgated, and the furniture industry moved aggressively in 1979 into a voluntary alternative program run by their Upholstered Furniture Action Council (UFAC). UFAC promoted industry use of cigarette resistant upholstery fabric and furniture design, testing protocols, and a hang-tag program. Those refinements have been incorporated into NFPA and ASTM voluntary standards based on PFF6-76. Most manufacturers of upholstered furniture follow this program and have changed furniture design, construction and materials so that resistance to cigarette ignition has improved greatly.

Today, using either government or industry data, it is widely acknowledged that deaths and injuries from cigarette ignition of upholstered furniture have declined dramatically. CPSC and industry data indicate that over 80 percent of currently manufactured furniture can be expected to resist cigarette ignition.

The issue of cigarette ignition has been, until recently, the main focus of CPSC's flammability investigations. CPSC data show that fire deaths due to cigarette ignition of upholstered furniture dropped from 1,150 in 1980 to 470 in 1994. Deaths from "small open flames" however, have remained consistent at about 100 per year during the same period, most of those deaths resulting from children playing with matches and lighters.

In 1998, CPSC issued a draft regulation which would require that a piece of upholstered furniture resist burning when exposed to a small flame for a period of 20 seconds. "Small open flame" is understood as meaning candles, matches, or cigarette lighters. It is further understood that in most cases, such fires are begun when children under the age of five play with matches, lighters or other sources of flame. The problem of small flame ignition continues to be studied.

It is noteworthy that strategies other than fabric flammability standards have been used with success in helping to reduce deaths, injuries and property loss due to fire. CPSC has issued a safety standard for matchbooks requiring the product to meet several design requirements, including locating the friction surface on the outside back cover near the bottom of the matchbook. CPSC has also issued a safety standard for cigarette lighters to ensure the child resistance of these devices. In addition, smoke detectors have come into widespread use in residences, and sprinkler systems are used increasingly, especially in multi-family residences.

The Department of Commerce recognized James Winger's contribution to this work with its award of the Silver Medal in 1978.

In all, the efforts have contributed to a very substantial reduction in deaths, injuries and property loss due to flammable fabrics. Accident data from all sources indicate reductions ranging from 50 percent to 90 percent in deaths and injuries involving children's sleepwear, mattresses and upholstered furniture.

11.2 FIRE SCENARIOS

The thrust of *America Burning* [1] was to solve the Nation's "fire problem," and the report set a goal of reducing U.S. fire losses by half in the next generation. In practice the Federal emphasis, at least as far as NBS was concerned, was to be on improving life safety rather than property protection. Ensuring life safety is primarily a regulatory exercise, and so from there it was an easy step to articulating CFR's own long-term objective: to provide the technical basis, particularly for the requisite codes and standards, necessary to cut fire deaths in half in 25 years.

Impressive as this objective may sound, however, it is useless as a managerial metric. For one thing, NBS had no control over its technology once in the hands of the actual regulator, whose mode of implementation and enforcement was crucial to reducing losses. Moreover, the time scale for reliably detecting any real change in fire statistics is of the order of several years, far too long to be of help in directing a research program day-to-day. Instead, the real utility of the loss reduction objective was in shaping the content of a research program. The formalism which was used to connect the two, loss reduction and program content, was the fire scenario.

A fire scenario is essentially just that: an abbreviated story or script of a fire. From CFR's point of view, it was the "who, what, where, when, how, and why" of the incident that was of most interest, because the physical aspects were the clues to where technology might have an effect. Although it was recognized that every fire would be different if described in enough detail, it was also suspected that, for fatal fires at least, there would be common elements in many scenarios which would point to ways of breaking the chain of events leading to the fatal outcome. This suggested a plan: devise a set of "intervention strategies" designed to address the most common fire death scenarios and fashion a research program based on those strategies.

First, however, it was necessary to determine just what the most common scenarios were. Fire departments were not required to keep statistics and, even if they did, there was no requirement that they be reported in any systematic fashion. Therefore, the first attempt at identifying the most common fire death scenarios was not databased at all but was the result of a Delphi exercise carried out by the CFR senior staff. Scenarios were described by occupancy, time of day, ignition source, item-first-ignited, agents of spread (both smoke and flame) and cause of death (heat or smoke). The Delphi-based scenario ranking was the basis for the Center first long range plan, completed in early 1975 [2].

There were those, however, who thought that a quantitative scenario ranking was not only preferable but possible. Clayton Huggett, then Chief of the Chemistry Section and later Deputy Director of CFR, was particularly insistent that it was worth trying. He persuaded Frederic Clarke, who was in charge of the CFR planning effort, to visit the National Fire Protection Association (NFPA), dig through the NFPA data files and see what could be accomplished.

NFPA had two distinct fire databases, both of which depend upon the voluntary cooperation of fire departments across the country. One, which was the forerunner of the National Fire Data System now operated by the Federal government, was based on a standardized reporting system and used for NFPA's annual estimate of U.S. fire losses. Fires and fire deaths were counted by occupancy, by time-of-day, etc., but there was no way at the time to relate the various categories, so the scenario approach wouldn't work.

THE TOP FIRE DEATH SCENARIOS

Rank	Occupancy	Item First Ignited	Ignition Source	% of Fire Deaths
1	Residential	Upholstered furniture /mattresses	Smoking materials	27
2	Residential	Upholstered furniture	Open flame	5
3	a. Transportation	Flammable fluids	Several	4
	b. Residential	Apparel	Heating and Cooking equipment	4
	c. Residential	Furnishings	Heating and Cooking equipment	4
6	a. Several	Apparel/flammable fluids	Several	3
	b. Residential	Flammable fluids	Open flame	3
	c. Several	Apparel	Open flame	3
9	a. Residential	Interior finish	Heating and Cooking equipment	2
	b. Residential	Interior finish	Electrical equipment	2
	c. Several	Apparel	Smoking materials	2
	d. Residential	Structural member	Electrical equipment	2
	All others, each less than 2 percent of total			34
				100

Also, it was recognized that fire departments under-reported deaths in certain categories, notably those from apparel fires, because the fire in question was often too small to generate an alarm. They also tended to miss deaths which occurred after the victim was transported from the fire scene.

NFPA's other database, the Fire Incident Data Organization, or FIDO, was strictly anecdotal. For an incident to be included in FIDO, it had to involve death, serious injury or large property loss. FIDO was subject to some of the same fire-department-derived biases as the regular NFPA data system but it had two important features: it was large, containing data on approximately 11,000 fatalities and there was a coded description of each fire incident, so it was possible to learn something of the circumstances of the death.

Clarke and John Ottoson, of NFPA, were able to cross-correlate the FIDO database and mortality data from the Bureau of Vital Statistics of the US Department of Health, Education and Welfare, both of which contained incomplete - but overlapping - profiles of US fire deaths, to produce the first self-consistent and completely inclusive estimate of where they occur. With this information in hand, the in-depth information from FIDO was used to produce a list of 14 abbreviated scenarios which together accounted for an estimated two thirds of US fire deaths [3].

Fire data collection has improved a great deal in the past quarter-century but these early estimates have proven to be surprisingly good. Comparison with the rankings produced by the Delphi exercise showed that the intuition of the CFR staff was reasonably accurate with one exception: the importance of children's sleepwear fires was overstated. Since the mid-70s were the height of Federal interest and involvement in this issue, such a finding should not be surprising.

The principal utility of fire scenarios, of course, is that they highlight where efforts need to be applied. That the ignition of soft furnishings by smoking materials, primarily dropped cigarettes, was an important scenario came as no surprise, but the sheer size of the problem was somewhat unexpected. It provided much of the impetus for the Center's work on upholstered furniture and mattress ignition standards; studies of room fire buildup and flashover; and the first systematic investigations of combustion product toxicology. In 1979, Benjamin Buchbinder received the Department of Commerce Bronze Medal Award for his work on decision analysis for fire safety.

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11.3 FIRE RESEARCH INFORMATION SERVICES (FRIS)

The Apollo I spacecraft fire in 1968 killing three astronauts was the first fatal accident of the United States space program [1]. This accident was

Nora Jason, leader, Fire Research Information Services

so tragic that the National Aeronautical and Space Administration/Aerospace Safety Research and Data Institute (NASA/ASRDI) developed a plan to have better access to information applicable to the program. Twelve areas of knowledge were identified. One of the areas was fire safety and the NBS, well known for its fire research and safety program and the reputations of Alexander Robertson and John Rockett, was selected for the project. The tasks were to create input for a bibliographic database and write several state-of-the-art reports.

The bibliographic database was designed to meet specific NASA needs and it was futuristic for its time, that is in the early 1970s. Each record had the complete bibliographic reference, and in-depth narrative abstracts, major and minor keywords, in addition to report number, corporate source, contract sponsor(s), contract number(s). It is now incorporated into the NASA bibliographic database.

No fire safety thesaurus existed in the United States or elsewhere so a vocabulary list (later serving as the nucleus of the FIREDOC Vocabulary List [2]) was developed to ensure quality control of the information to assist the user.

The state-of-the-art research reports discussed topics such as fires in oxygen-enriched atmospheres, fire detection, and toxicity. In addition, a list of experts in the fire field [3] was developed to be a additional source of information.

There was no fire research library in the United States and NBS recognized that the NASA work could be a model for a fire literature collection. The decision to develop and maintain a fire research literature collection was recommended by the National Academy of Sciences [4]. Dick Katz was the selected as the first project leader of the Fire Research Information Services. Shortly thereafter he was transferred to the newly formed U.S. Fire Administration library and Nora Jason became the project leader.

The first NBS product was the annual compilation of fire research reports [5]. Over time this product continued to incorporate the technological changes and the organizational changes [6]. Nora Jason's work in establishing FRIS was recognized by the Department of Commerce Bronze Medal Award in 1976.

The first CD-ROM containing fire research publications [7] by the staff and grantees was created in 1993; by the following year the CD-ROM [8] included building staff contributions. S. Regina Burgess's scanning ability and Glenn Forney's computer skills have enhanced the product. The BFRL yearly bibliography in paper format ceased in 1996 and only the CD-ROM version was available. In 1997 the digital version of all BFRL publications became available on the NIST web site http://www.bfrl.nist.gov and listed in the section entitled BFRL Publications Online.

In 1986 FIREDOC, an online bibliographic fire research database [9], was first announced at the Society of Fire Protection Engineers' Annual Conference in Atlanta, Georgia. By 2000 Kathleen Whisner has devoted approximately 13 staff-years inputting 60,000 bibliographic records into the database. Initially it was accessed over telephone lines and telnet. In 1996 FIREDOC became available over the World Wide Web and today that is the sole source of entry; the URL is: http://fris.nist.gov. The effectiveness of FRIS' Fire on the Web was recognized in 1999 by the Bronze Medal Award of the Department of Commerce for Nora Jason and Glenn Forney.

The original NASA tasks set a precedent for additional work with NASA and other organizations in creating bibliographies and organizing conferences and editing conference proceedings [10]. Other agencies/organizations with projects that involved the FRIS staff included the Minerals Management Services, National Fire Protection Association Research

Foundation, and the U.S. Fire Administration.

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11.4 FIRE INVESTIGATIONS AT NIST

11.4.1 INTRODUCTION

Serious fire by its natural is a large-scale event, and difficult to reproduce in laboratories, even in large laboratories. The study of real world fires provides the opportunity to test, evaluate and demonstrate the engineering tools developed by NIST and its colleagues around the world and to determine the efficacy of the various standard approaches included in building codes and other engineering regulatory and guide documents.

Ever since fire research became a NIST program in 1914, NIST has been interested in fires and have made investigations and evaluations of incidents. A formalized approach to investigation, however, did not get underway until the mid 1970s, and then at a relatively slow pace. Fire investigation is one of the responsibilities contained in the Fire Prevention and Control Act of 1974 [1]. NIST's initial response to this obligation was to award a grant to the National Fire Protection Association underwriting increased activity in their established fire investigation activates. The NFPA investigations, while important, concentrated on the construction, fire department activities and conformance with established codes and standards. They did not undertake engineering calculations or try to quantitatively analyze the fire phenomena. The situation is understandable when it is recognized that until the late 1980s there were few publicly available instruments for making such evaluations. One of the best of that era was the Fire Investigation Handbook [2] published in 1980. It however faded into virtual nonuse once the models and other analytical tools became available. For its time the Handbook was great but late and soon passed-over by fire technology advances. During the 1990s the Fire Safety Engineering Division was involved in the investigation and analysis of several large fire disasters around the world.

11.4.2 NURSING HOME FIRES

In 1975 NIST was charged by the Department of Health and Human Welfare formerly the Department of Health Education of Welfare (HEW) to improve the firesafety knowledge base in nursing homes. There had been a series of serious nursing home fires and Congress had passed an act mandating that nursing homes conform with the Life Safety Code published by NFPA. The desire of HEW was to go beyond this and develop a better understanding of the life safety problems in nursing homes and develop better means of responding to them. One of the initial NIST efforts was a study undertaken through a grant to the University of California at Berkley, with Professor Lars Larup as the principal investigator. Professor Lerup studied the available data. His primary source was NFPA reports of serious fires in nursing homes.

Working closely with the NIST staff he made parallel plots of the development of the fire and resulting fire hazard in comparison with the activities of the staff and patients. He presented these in graphic/realistic cartoon fashion [3]. Lerup's work brought out a number of observations important to safety to life that had not been previously detected. Of single most importance was the fact that nursing staffs did not understand the phenomena of flashover and the danger of allowing a flashover fire to vent itself inside the building. Both HEW and NIST agreed that it was important that nursing staffs be informed of flashover, its dangers, and safeguarding actions they could undertake. As a result NIST produced the training film Flashover, Point of No Return [4]. Flashover, Point of No Return demonstrated the risk of flashover, the impact of the phenomena, and the ability a nursing staff had to confine the fire using the traditional hospital patient room door. Flashover was first published in the late 1970s and is still actively used as a training tool. Hundreds of thousands of nursing staff have viewed it and indications are that it has resulted in incidents where the nursing staff followed its guidance and protected the residence of nursing homes from a potentially lethal insult. Both Lerup's analysis and Flashover received national recognition in the form of awards.

11.4.3 FIRE INVESTIGATION HANDBOOK

The Fire Investigation Handbook [2] was unique for CFR in that it was not based on original research at CFR. Instead, CFR performed an editorial and implementing function to prepare a handbook for fire investigators. Its separate sections were written by practicing experts under editorial guidance from Francis Brannigan, an eminent practitioner, and Richard Bright and Nora Jason of CFR. The whole handbook was reviewed by other experts and the U.S. Fire Administration. All of the contributors donated their contributions.

The sections are: Fire Ground Procedures, Post-Fire Interviews, the Building and its Makeup, Ignition Sources, the Chemistry and Physics of Fire, and Sources of Information. In addition there are appendices on how to organize an arson task force, how to be an effective expert witness, a list of independent testing laboratories, and a bibliography. The handbook was published by the U.S. Government Printing Office on paper that would survive moisture and rough handling in field use. It was reprinted at least twice.

11.4.4 ADVENT OF MATHEMATICAL POST FIRE ANALYSIS

At the time Lerup produced his graphic displays there were no available mathematical compartment fire models available to describe the fire. Lerup's work was primarily based on fire reports and the qualitative understanding of fire provided by the staff of the Center for Fire Research. Mathematical models, however, at that time were beginning to emerge from several sources, sponsored by NIST. This includes grant work by Edward Zukoski at California Institute of Technology, the work of Howard Emmons and his colleagues at Harvard and the Factory Mutual Research Corporation, and the work of Thomas Waterman and Ronald Pape at Illinois Institute of Technology. All of these came to fruition at about the same time. Each was different in its detail while following the same general concept of entrainment of gases (air, smoke, etc,) into the flame and fire plume, heat balance, radiation, and fluid (smoke) flow. Also about the same time the concept of oxygen depletion calorimetry also was developed. This development was primarily through the efforts of William Parker and Clayton Huggett at NIST. Their work resulted in a breakthrough in the determination of mass burning rates and rates of heat release of both individual materials and full size furniture assemblies.

With the availability of these new tools and the associated knowledge, it became feasible to make scientifically based quantitative analysis of the fire phenomena and to reconstruct the course of the fire and the reasons that a fire behaved as it did. The first efforts focused on specific occurrences during the fire, latter the scope was expanded to a more universal appraisal. Improvements in both scope and quality of scientifically based fire investigation continue to this day.

NIST has been involved in a large number of fire investigations. A selected series of investigations are listed to demonstrate the progression in increased sophistication with time.

11.4.4.1 Beverly Hills Supper Club, 165 Fatalities, May 18, 1977

One of the first application of the new analytical knowledge to fire investigations occurred in the litigation resulting from the Beverly Hills Supper Club Fire on May 18, 1977. One hundred and sixty-five persons died in this fire. The Beverly Hills Supper Club was a large complex with several different activities. These included a traditional dining room restaurant, a cabaret, and a separate bar. The fire started in the bar and, at a point early in the fire, spread with great speed to the cabaret room where the majority of the deaths occurred. It was initially held that fire spread on the surface of combustible material through a corridor linking the bar to the cabaret space. Howard Emmons, a close colleague and grantee of NIST at Harvard University analyzed the fire phenomena involved, Emmons used the phenomenology developed as part of the work he and his team at Harvard and Factory Mutual Research Corporation were undertaking as part of a NIST grant covering the development of fire models. Emmons demonstrated that the fire spread as fast as it did not because of a progressive ignition on a combustible surface, but rather as a fluid mechanics movement of a flame front containing yet unburned pyrolized products. The flame and fuel moved as a fluid transported down the corridor from the bar to the cabaret.

11.4.4.2 MGM Grand Hotel and Casino, Las Vegas, Nevada, 84 Dead, November 21, 1980

In the MGM Grand Hotel Fire John Klote acting as the advisor for NIST, used his work on smoke travel to identify the paths of smoke movement from the fire source at ground level to the various upper levels of the building. The enclosures around the earthquake joints and the elevators were found to be the prime source of smoke and toxic gas movement. Also, post-fire evaluation of the chemical content of victims blood, by Merit Berky, lead to a conclusion that the carbon monoxide (carboxyhemoglobin) was not sufficient to be the sole source of fatality and there was strong suspicion of hydrogen cyanide presence in the smoke distributed throughout the building.

During the litigation following the fire, Emmons was again retained as an expert witness and used the Harvard V model, recently developed, to demonstrate which of the materials in the kitchen and dining room area, where the fire started, contributed to the development of flashover and which did not.

11.4.4.3 Hospice of Southern Michigan, 6 Dead, December 1985 [5]

This analysis was the first attempt by the NIST staff to use fire modeling to reconstruct a fire incident. The actual field investigation was conducted by the NFPA fire investigators. The subsequent analysis by NIST. The fire models used in the analysis were ASSETB [6] and DETAC T[7]. In this incident, a fire occurred in a bedroom off a corridor. The bedroom door was open. The window broke as the room went through flashover, and smoke progressed down the corridor invading other rooms. The initial appraisal of the carbon monoxide content in the atmosphere flowing into the exposed rooms down the corridor appeared to be marginal in its lethality. However, all of the exposed patients died. Since this was a hospice it was first felt that the terminal conditions of the patients made them extraordinarily susceptible. Autopsies however, indicated that almost all of the victims had high carboxyhemoglobin concentrations in their bloodstream, indicating that their personal health condition was not a factor. As a result of this inconsistency, Nelson conducted an experiment in the NIST burn test corridor where the arrangement of spaces was reconfigured to imitate the situation at the hospice. In the fire air was drawn in through the broken window of the room of fire involvement. This sustained a flashed over high-energy fire. The fire vented smoke laden with carbon monoxide and devoid of oxygen into the corridor which spread into the sleeping rooms. The result of this test demonstrated a massive switch in the chemical balance between carbon monoxide and carbon dioxide, producing conditions 30 times to 100 times more lethal than free and open burning with adequate air. Further testing at NIST continues to this day and has demonstrated the appropriateness of this conclusion.

11.4.4.4 Dupont Plaza Hotel, Puerto Rico, 90 Dead, December 31, 1988

This is the first incident in which NIST used its emerging analytical techniques and models to describe the course of events in fire. James Quintiere and. Nelson joined the Federal investigation team working at the site. Their prime purpose was to both assist the Alcohol, Tobacco and Firearms team and to demonstrate and test the ability of the computational instruments then arriving on the scene.

Nelson used the collection known as FIREFORM [8]. FIREFORM included various closed form equations related to fire and Nelson's partially completed compartment fire model (then called ROOMFIRE, but later entitled FIRE SIMULATOR). With these the NIST team was able to demonstrate the speed of development of the fire as well as its production of excess pyrolstate (unburned fuel) mixing with the flames. The transfer of this flaming mixture of burning yet unburned combustible material from the ballroom, where the fire occurred, into the large foyer and from there traversing the casino, where the majority of the deaths occurred was determined by Quintiere and Nelson. The reconstruction developed by the NIST team was found to be in very close proximity with the findings made by ATF and FBI through interviews and matched very closely with photographs taken during the fire. It's felt this investigation was a breakthrough investigation in terms of advancing the concepts of fire reconstruction with physical and mathematical models. Jack Snell was awarded the Gold Medal of the Department of Commerce in 1987 for overall leadership of the investigation and for subsequent efforts to modernize Puerto Rican regulations for the fire safety of buildings.

The engineering tools used in this evaluation have been refined and brought together in the collection FPETOOL [9]. The FPETOOL collection and other models are now heavily used throughout the entire fire safety community in both risk appraisal and fire incident reconstruction. Prime examples of the advances being made are the use of Computational Fluid Dynamics (CFD) fire and smoke models in the reconstruction of events in the Cherry Road Fire and the work currently underway in understanding the events resulting in the collapse of the World Trade Center attack on September 11, 2001.

Also, as a result of the demonstration of the value of engineering analysis and fire science to fire investigation, the ATF has undertaken a serious effort to train its fire investigators in the rudiments of fire science, added fire protection engineers to their staff and is in the process of the construction of a major new fire test and investigation laboratory.

11.4.4.5 First Interstate Bank Building, 1 Dead, May 4, 1988 [10]

One person died in this fire. This fire initiated in the trading room on the twelfth floor of a 60 story building. While sprinkler protection was in the process of being installed, it was not in service at the time of the fire, so the building responded as a non-sprinklered building. The fire traveled from floor to floor, presumably through the space between the exterior wall and the floor slab, eventually covering four floors. Problems with the water supply hampered the fire department and the fire burned unattacked for almost two hours. The fire propagated around the entire building on each of these floors and was fully involved for the entire floor areas for most of its duration. The probable point of origin was mathematically determined by the sequence of response of the smoke detectors and the characteristic burns of the living contents. The models in FPETOOL were used and proved capable of analyzing the fire development and spread on any floor. The spread from floor to floor was, however, estimated on the physical evidence of the flame and empirical understanding of the construction of the joints between floor slabs and curtain walls. The building survived with complete

First Instate Bank Building. BFRL develops improved methods to evaluate fire performance of new materials and structures.

burnout of the involved floors, but no structural damage or failure of a load-supporting member.

11.4.4.6 Hillhaven Nursing Home Fire, 13 Dead, October 5, 1989 [11]

In this fire 13 persons died. The fire was reminiscent of the conditions previously described for the hospice of Southern Michigan. A flashed over fire occurred in a bedroom, the patients from that room were removed to a place of safety, but the doors on the other patient's rooms failed to close properly and the carbon monoxide loaded gas propagated through the corridor, entering these rooms and killing patients in their beds. The importance of this investigation has been an impact on the fire investigation field. The report lays out step-by-step the engineering analysis of the incident starting with the ignition of the initial fuel and proceeding to the final end result. The report is used in numerous fire investigation courses as an example of a methodology to be emulated.

11.4.4.7 Happy Land Disco, Bronx, New York, 87 Fatalities, March 25, 1990 [12]

In this fire an arsonist splashed gasoline over the entrance to the building. It was estimated about 3.8 L of gasoline was used. The fire was then ignited, it flashed over the foyer, followed by flashover of the adjacent barroom and then raced up stairs, pushing toxic fumes ahead of it, until it filled the upstairs main room with toxic fumes. Relatively small amounts of flame actually reached the upstairs. The fire scene was investigated by Richard Bukowski and Harold Nelson and the model FAST [13], then in its final pre-release stage of development at NIST, was used to reconstruct the process and progress of the fire. The model demonstrated the manner in which oxygen was depleted in the original space of involvement, resulting in the production of high carbon monoxide, which rapidly anesthetized and then killed the occupants of the second floor.

11.4.4.8 Oil Fields of Kuwait

As a result of the Iraqi invasion of Kuwait and the subsequent conflict, 749 oil wells were systematically damaged with explosives in February 1991 resulting in uncontrolled gas and oil well blowout fires on 610 of the wells. As part of the international scientific response to the environmental and health emergency, NIST in coordination with the United Nations Environment Programme (UNEP), the World Meteorological Organization (WMO), the U.S. Army Corp of Engineers, and U.S. Gulf Environmental Technical Assistance Task Force, performed exploratory

Daniel Madrzykowski, fire engineer, is performing heat flux measurements. The flame height is about 65 m high with a heat release rate of 1.7 GW.

measurements to demonstrate the feasibility of determining the heat release rate of burning wells as an essential part of the characterization of the fires for use in modeling of the smoke plume[14].

Dave Evans, Dan Madrzykowski, and George Mulholland traveled to Kuwait in May 1991. Flame height and heat flux measurements were made on a number of burning oil wells in the Al Mawqá and Al Ahmadi oil fields [15]. Smoke samples were also collected. Gerald Haynes provided NIST with an aerial flame height survey of burning wells in the Al Minagish oil field. A radar altimeter was used from a helicopter to perform this measurement. The heat release rate of the fires measured ranged from 90 MW to 2,000 MW that corresponded to 1,500 barrels to 30,000 barrels of oil per well per day.

11.4.4.9 Oakland Hills

On Sunday, October 20, 1991, Oakland California experienced one of the worst single fire losses events in recent U.S. history. Twenty-five persons were killed and 2,889 dwellings were destroyed. The conflagration, which covered 7.2 km2, was a classic example of a wind driven, wildland/urban interface fire [16]. Kenneth Steckler, David Evans and Jack Snell comprised the NIST team who worked with fire experts from Japan, the U. S. Department of Agriculture, and UC Berkeley. The objective of the investigation was to determine the role that wood framed structures played in the fire spread. The investigation found that the high wind speed, proximity of flammable vegetation to structures and the flammability of exterior construction materials were factors in the spread of the fire. The use of wood framing members did not significantly influence the rate of spread or the extent of the fire [16].

An Oakland Hills neighborhood that was in the fire's path and completely destroyed. Note the burned automobiles in the foreground.

11.4.4.10 Post-Tsunami Fires, Hokkaido, Japan

On July 12, 1993, an earthquake registering 7.8 on the Richter scale struck in the Japanese Sea off the coast of Hokkaido. The earthquake generated a tsunami that devastated the small island of Okushiri. The tidal wave destroyed buildings, overturned fuel tanks and spread debris making it difficult for the fire department to respond to the fires that followed the tsunami. The disaster resulted in more than 200 people dead and more than $60 million dollars in damages. By the time the fires were extinguished almost 300 homes had been destroyed. Through the effective bilateral collaborative US-Japan Program on Natural Resources (UJNR), which includes a Panel on Wind and Seismic Effects and a Panel on Fire Research and Safety, Noel Raufaste of NIST and Kazuhiko Kawashima of the Japan Public Works Research Institute (PWRI) quickly organized teams to investigate the damages and what might be done to mitigate future disasters of this type. Richard Bukowski, of NIST, and Charles Scawthorn, of EQE International, headed the fire portion of the investigation [17]. The study found that the combustible construction of the buildings, combustible debris between the buildings and the unanchored kerosene and propane tanks all contributed to the fire spread. Comparisons were made between the events of these post-tsunami fires to the post-earthquake fires that occurred in the 1980s after the Coalinga, Loma Prieta and San Francisco earthquakes.

11.4.4.11 Post-Earthquake Fires, Northridge, CA

A magnitude 6.8 earthquake struck the San Fernando Valley at 4:31 AM on January 17, 1994. Fifty-eight people died and thousands of injuries resulted

A collapsed carport shields a house from the adjacent structure that burned down completely.

from the earthquake. Building damage was wide spread with approximately 80,000 people to 125,000 people displaced from their homes. In the most severe cases, buildings and elevated highways collapsed. The earthquake also resulted in 30 to 50 significant fires throughout the valley and an increased number of fires in the days following the earthquake due to restoration of power and gas to damaged buildings. A multi-agency team, organized under the auspices of the Interagency Committee on Seismic Safety in Construction and headed by the NIST, was assembled and within days of the incident were working at the disaster locations [18].

Doug Walton led the fire portion of the investigation for NIST. His focus was to identify the factors that contributed to the cause, spread of and loss from the fires. The finding of the study indicate that a significant number of the post earthquake fires involved natural gas leaks due to damaged lines or equipment. Due to light winds, high moisture content in natural fuel, building construction and spacing, and the intervention of the fire department most of the fire were limited to the building of origin. However building-to-building fire spread did occur in three manufactured housing developments. In these developments, close spacing and combustible construction lead to multiple unit fires. In some instances, the collapse of carports between units helped to form a firebreak. In addition to documenting what happened, the poster disaster report states that given the favorable weather conditions and the time of the occurrence, the fire losses were small relative to the loss potential under windy, hot and dry conditions [18].

11.4.4.12 Post-Earthquake Fires, Kobe, Japan

A year to the day, after the Northridge, CA earthquake, an earthquake of similar magnitude struck Kobe, Japan and its surrounding areas. The earthquake resulted in more than 6,000 deaths and over 30,000 injuries. The multi agency investigation was conducted under the auspices of the UJNR Panel on Wind and Seismic Effects. The objectives were to document important lessons from this earthquake that might be used to mitigate the impact of future earthquake disasters [19].

From the U.S., the fire team was composed of Dan Madrzykowski from NIST and Ed Comeau from the National Fire Protection Association. They were in Japan from February 12 through 18, 1995. One hundred forty eight fires occurred during the three days following the earthquake. The fires damaged or destroyed approximately 6,900 buildings and burned the equivalent of 70 city blocks. The source of many fires were broken gas lines and damaged kerosene heaters. Many of the ignitions occurred as electric power restoration was attempted. Collapsed buildings intermingled with crushed automobiles assisted the fires in spreading from block to block. The damage in Kobe to the water supply,

An example of the many collapsed buildings that blocked entire streets making it difficult for emergency response on in some cases, escapes. If this building had caught fire, it would have easily spread the fire to both sides of the street and exacerbating the fire conditions considerably.

the emergency water cisterns, and to the transportation systems (highways, train trestles, etc) significantly limited the fire department response. Lessons learned for the U.S. covered a broad range. Beginning with large scale governmental issues, such as city planning and design to develop fire breaks and alternative water supplies and ending with information and training for residents so that they can be prepared to help themselves in times of widespread disasters that overwhelm public service resources.

11.4.4.13 Cherry Road Fire, Washington, D.C, 2 Firefighter Fatalities, May 30, 1999, [20]

NIST was asked to help on the Cherry Road Fire Investigation by the District of Columbia Fire & Emergency Medical Services Department Reconstruction Committee. The reconstruction committee could not explain several things about the fire incident.

1. Three firefighters received severe burn injuries that seemed to be inconsistent with the limited thermal damage in the room they were in.
2. The severe burn injuries to the three firefighters were inconsistent with the minor injuries to other firefighters that were in close proximity.
3. The two nozzle men, both fatalities, were well trained and adequately equipped. Why didn't they flow water from their charged (pressurized) hose lines to protect themselves?

Two NIST models, the Fire Dynamics Simulator [21] and Smokeview [22], were used to simulate and visualize a townhouse fire that claimed the lives of two Washington D.C. firefighters. A model following the Standard Operating Procedures (SOPs) of the fire department for comparison purposes was also developed.

The Fire Dynamic Simulator simulations and the Smokeview visualizations helped the department understand the incident. It also demonstrated the value of the departments SOP relative to venting. The CD-ROM format allowed research results and fire modeling technology to be used directly by the fire service (i.e. a training officer can take the CD and use it to demonstrate the benefits of proper ventilation, the speed with which a fire environment can drastically and tragically change).

The results are being made available to a wide audience to educate firefighters in an effort to prevent a similar incident from occurring. NIST engineers developed a CD-ROM demonstrating the application of the models to this case [23]. The Smokeview visualizations have been incorporated into a number of fire fighter training curriculums, including IAFC's Command School, the National Fire Academy. As discussed below these models are cornerstone elements in the ongoing analysis of the fire development in the World Trade Center attack of September 11, 2001.

NIST staff engineers, Daniel Madrzykowski, Robert Vettori, Doug Walton, Glenn Forney, and Kevin McGrattan, formed the team that enhanced the existing models, applied then to the problem and presented the results in a manner meeting the needs of the investigation.

11.4.4.14 Summary

The sophistication, quality, and impact of NIST fire investigations have massively increased over the last decades. Investigations have become an important test of and technology transfer instrument for dissemination of NIST products.

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11.5 SMOKE AND FIRE DETECTORS

A summary of early work at NBS was prepared by Dan Gross for the third IAFSS Conference in 1991 [1]. The earliest studies at NBS of the performance of detectors were conducted in the 1920s and 30s. In the 1950s pioneering work was conducted by McCamy on flame detectors for aircraft engine nacelles [2] in which he published data on both ultraviolet (UV) and infrared (IR) signatures and proposed coupling IR sensors with flame flicker circuits to discriminate hot objects from actual flame.

11.5.1 OPERATION BREAKTHROUGH

In the late 1960s the US Department of Housing and Urban Development (HUD) instituted a major, innovative housing demonstration project called "Operation Breakthrough" [3]. Intended to facilitate the development of novel approaches to design, materials, and construction techniques for improving low-income housing, the program included the submission of concepts and the actual construction of demonstration homes by the winning submitters. Because traditional, prescriptive building codes could not deal effectively with innovative methods and materials, HUD engaged NBS to develop performance-based guide criteria to assure safety, functionality and durability of the innovative systems. The guide criteria were a prototype for the performance standards now being promulgated globally. HUD obtained waivers of local prescriptive building codes to allow construction and occupancy of the demonstration homes.

At the time of Breakthrough, fire alarm systems in homes were rare, and where installed used commercial detectors and panels designed by the rules applied to commercial properties. Heat detectors usually were used in occupied spaces. In commercial installations, relatively expensive smoke detectors usually were used only to protect high value items, so they were rare in home systems. A then typical residential system cost as much, in 1968 dollars, as residential sprinkler systems cost in 2000 dollars. The (single-station) smoke alarm had been developed in 1965 but sales were low and availability poor for the few models being marketed.

One of NBS's fire protection engineers, Richard (Dick) Bright, had been impressed with an article published by Canada's National Research Council in 1962. John McGuire and Brian Ruscoe [4] studied 342 residential fire deaths in Ontario from 1956-1960 and judged the life saving potential of a heat detector in every room or a single, smoke detector outside the bedrooms and at the head of the basement stairs (if the home had a basement). Their judgment was that the heat detectors would have reduced the fatalities by 8 percent and the smoke detectors by 41 percent.

NIST included in its Breakthrough criteria [5] a requirement for smoke detectors located in accordance with the McGuire and Ruscoe guidelines. Since few of these homes were built, no substantial fire experience was gained with these detectors.

11.5.2 HURRICANE AGNES

In 1971, heavy rains from Hurricane Agnes flooded many homes in central Pennsylvania and lower New York. HUD mounted a federal disaster relief effort (this was before FEMA was created) including the provision of temporary housing for many poor residents of the region. HUD purchased 17,000 mobile homes (later called manufactured homes) and asked NIST to apply some of the lessons of Breakthrough to the purchase specification. NIST included a requirement for a single-station smoke detector (typically battery operated) outside the bedrooms of each unit. The order for 17,000 smoke detectors had to be split among five manufacturers because at the time no single company had the production capacity to fill the order. Today, one manufacturer could do so with two days' production.

The 17,000 homes were delivered to several sites and were used by families until they could rebuild or find alternative accommodations. Most lived in the homes for a year but some were still occupied three years later. The fire safety statistics were surprising. While the statistically expected number of fires did occur, there were no fire deaths and few injuries. The smoke detectors were credited with getting occupants out before they became trapped - just as McGuire and Ruscoe had surmised.

This was the first, large installation of residential smoke detectors and the results convinced the manufactured housing industry to adopt the first smoke detector "ordinance." In 1975 it became the policy of the Mobile Home Manufacturing Association (the predecessor of today's Manufactured Housing Institute) that one smoke detector located outside the bedrooms be provided in every manufactured home produced by a member company.

11.5.3 UL STANDARD

The large procurement of smoke detectors for the hurricane Agnes homes piqued Dick Bright's curiosity about just how well these devices performed in detecting fires. He modified a spare prototype of the NBS Smoke Chamber (that later became ASTM D648) to generate smoke from a small source and circulate it with a small bar heater. When he hung production smoke detectors in the box he was appalled to see the "power on" light on many disappear in the smoke without a sound from the detector.

Further tests revealed a problem with smoke entry into the outer housing at low convective flow rates. The smoke box test used by Underwriters Laboratories (UL) at the time had two large fans pointed directly at the detector forcing the smoke in - a not so realistic condition. This experience led Bright and his supervisor Irwin Benjamin to conclude that the potential of residential smoke detectors would not be realized unless there were effective product approval standards that assured their proper performance and reliability.

Bright and Benjamin approached UL about participation in a cooperative project under NBS' Industry Research Associate program where UL would assign an employee to work at NBS for a year to develop the basis for such a standard that UL would then promulgate. Richard Bukowski was selected by UL for the one-year assignment, beginning in the fall of 1973.

One of the unique aspects of this project was that it was conducted in close cooperation with the residential smoke detector industry, who themselves were working with an immature technology. Companies provided samples of current product and were very grateful for constructive criticism. Company engineers began to visit with prototypes of models under development that were jointly evaluated and improved. This cooperative environment led to rapid improvements in the performance of detectors that benefited the public and the industry.

The work that year uncovered a number of issues identified as problems (or potential problems) that were corrected by the industry and incorporated in the suggested standard that was presented to UL and formed the basis for the first edition of their Safety Standard for Single- and Multiple-Station Smoke Detectors, UL217. These included:

- Identification and quantification of low velocity smoke entry problems into detector housings or sensor assemblies and the associated Variable Velocity and Directionality tests in the new Standard.
- Design of a new smoke box for sensitivity testing with improvements to the flow characteristics and instrumentation that is now used for all smoke Detectors.
- Effects of the condensation of moisture on sensor or circuit boards that could cause false alarms or non-operation and the Humidity Plunge test placed in the Standard to address this issue.
- Development of an electrical transients test to improve reliability by reducing the susceptibility of detectors to damage from transients.
- The application of the "full-scale fire tests" to all smoke detectors where they had previously been used only for ionization type.
- Agreement on the policies of minimum one-year battery life, including the battery with the detector at purchase, the use of commonly available batteries, functional testing features, and others.

11.5.4 NFPA STANDARD

In the fall of 1974, Bukowski returned to UL and completed the development and adoption of UL217. Bright had been appointed Chair of the National Fire Protection Association (NFPA) Committee on Household Fire Warning Equipment that developed the NFPA 74 Standard on the Installation, Maintenance, and Use of Household Fire Warning equipment. First published in 1967 as a guide for homeowners this document reflected the philosophy of the times that homes should be protected in the same way as commercial businesses - with a heat detector in every room wired to a fire alarm panel and alarm bells. The cost of such a residential fire alarm system for an average home was about $1500 so they were rare.

Since the installation of residential fire alarm equipment was voluntary (and no one thought that requiring fire safety equipment in homes would ever happen), Bright felt that homeowners should be given the opportunity to choose a minimum system that provided some protection at low cost, like that suggested by McGuire and Ruscoe. The committee proposed a system of four "Levels of Protection" in the 1974 edition of NFPA 74. These were:

Levels of Protection

- Level 4 was a smoke detector outside the bedrooms and at the head of any basement stairs from McGuire and Ruscoe.
- Level 3 added heat or smoke detectors in living or family rooms that had the highest statistical likelihood of residential fire initiation.
- Level 2 added heat or smoke detectors in the bedrooms that were next on the list of fire initiation.
- Level 1 was the full system of a heat or smoke detector in every room.

This unique concept was presented to the NFPA Membership for adoption at the May 1974 meeting in Miami Beach and it was strongly opposed by the fire services (the Fire Marshals and Fire Chiefs). Their concern was that they saw no evidence that anything less than "complete protection" (Level 1) was adequate. They were correct - the levels were solely based on the judgment of the committee and that of McGuire and Ruscoe.

11.5.5 INDIANA DUNES TESTS

While the Levels of Protection concept was adopted at that meeting the concern expressed by the fire service were not taken lightly. Bright proposed that NBS fund a research project, which came to be known as the Indiana Dunes Tests, [6] to assess the effectiveness of the Levels of Protection. This contract was awarded to IIT Research Institute and UL. The Principal Investigators were Tom Waterman of IITRI, and William Christian and Bukowski from UL.

Detectors currently available on the market were installed in actual, unoccupied homes that were scheduled for demolition and available for fire tests. Fires involved actual residential contents and instruments monitored conditions within the homes to judge when unassisted escape using doors (but not jumping out windows) would no longer be practical.

The research involved 76 experiments conducted in three homes over two years. The data showed that the optimum performance was obtained with a smoke detector on every floor level of the home, mostly because smoke flow up stairs could be impeded by flows induced by HVAC systems, especially air conditioning. A closed door at the top of the basement stairs could create a dead air space that delayed response. The home was better protected from fires starting in the basement by a smoke detector on the basement ceiling near the stairway.

The report presented results in a unique way, in terms of the escape time (time between detector alarm and reaching one of the tenability limits defined by the study) provided by the detectors. These escape times were used to produce a probability plot of the percent of experiments in which a given amount of escape time was provided. Thus the reader could select a time needed and determine the percent of cases in which that (or more) time was available.

In an independent analysis of the first year results, a fire safety panel, advising the governor of Massachusetts on a statewide detector law, applied an arbitrary three-minute escape time requirement. The data showed that a smoke detector on every level would provide the required three-minutes in 89 percent of the cases, while a smoke detector in every room would increase meeting the requirement only to 93 percent.

In 1978 the US Department of Housing and Urban Development (HUD) commissioned a study similar to the Indiana Dunes Tests to be conducted in a manufactured home [7]. HUD was preparing to promulgate their federal Manufactured Home Construction and Safety Standards (49CFR3280) and this work provided the basis for the smoke detector requirements therein.

11.5.6 REGULATORY ACTIONS

The Indiana Dunes tests had a strong and immediate impact and soon various jurisdictions began to adopt laws requiring the provision of smoke detectors in every level of new residential housing. More surprising to many was the adoption by some of regulations requiring the installation of smoke alarms in existing residences. This ran counter to the U.S. tradition of "a man's home is his castle;" most opposition was not to the smoke detectors, but to the challenge to this tradition. Montgomery County Maryland was one of the first to adopt such an ordinance in 1975, effective in 1978. Even more startling was the immediate impact of the law. As implementation began the residential fire death rate, which had been steady for some years at around 32 per year, began to drop significantly. After the law became effective fatalities became zero in compliant homes and stayed there for several years; this convinced other jurisdictions to adopt similar laws.

Successes like that of Montgomery County led to the rapid adoption of mandatory smoke detectors in most state or provincial building codes in the U.S. and Canada. Codes at the city or county level often went further by requiring the installation of smoke detectors in existing residential properties. Coupled with effective marketing campaigns by major appliance manufacturers such as GE and Gillette, and retailers like Sears, compliance with these regulations was unusually high - typically above 90 percent. The result was a decline in U.S. fire deaths by 50 percent between 1975 and 1998 that has been attributed largely to the smoke detector.

11.5.7 FURTHER STUDIES

The "Indiana Dunes Tests" and other similar studies conducted in the 1970s and 80s clearly demonstrated that the occupants of most homes with smoke detectors at every level could expect 3 minute to 5 minutes of escape time for most fires. However there were several human factors questions such as how effective smoke detectors were at awakening sleeping people and how much time was needed for a family, especially with young children, to escape.

To address these issues NBS awarded a grant to Professor E. Harris Nober at the University of Massachusetts at Amherst to conduct a study. Nober had a sleep laboratory on campus and experience in this field, although like most sleep researchers he had focused on insomnia as opposed to awakening. Nober's work [8] began in the laboratory but soon moved into homes to provide more realism and to address the behavior of whole families. He developed a protocol to install in a test home a smoke detector that could be activated with a radio transmitter from the street. After waiting several weeks to avoid biasing the trial, the researchers activated the alarm in the middle of the night. The family had been instructed to turn on a bedroom light immediately on awakening (this gave a measure of awakening time), to place a call to the Amherst Fire Department (which participated in the study and provided a time for the call), and to evacuate outside to a pre-arranged meeting place in front of the house. These experiments it determined that three minutes, as judged almost a decade prior, was a typical evacuation for families.

In the early 1980s NBS decided that the residential smoke detector issues had largely been addressed and the technology matured. Product approval standards (UL217) and installation standards (NFPA74) were in place and the combination of regulatory and voluntary installations were at a pace that soon nearly every home would be equipped. Thus, NBS decided to apply its limited resources in other areas.

The result was limited studies mostly aimed at improving detector performance in special applications. The applications addressed included health care facilities [9, 10] (especially reducing the incidence of nuisance alarms that were affecting system credibility), fire protection for atria [11] (these had become a common architectural feature), and even spacecraft [12]. NASA had begun advanced planning for their 21st Century projects, including a space station, and wanted to explore innovative techniques for fire detection.

In the 1990s NIST (formerly NBS) pioneered the use of computational experiments to study the performance of, and to develop guidelines for the installation of, smoke detectors. In a project funded through a public/private consortium through the (National) Fire Protection Research Foundation, NIST researchers evaluated the effects of both geometry and physical barriers, and the interaction with mechanical ventilation systems on smoke and heat detector activation times. While others have used computational techniques to design specific installations, this was the first time anyone performed parametric calculations designed like a series of experiments to provide systematic information on a hypothesis.

The results of the study were revealing; confirming some common practice and indicating that some assumptions may be wrong. The results had a direct and significant effect on the code requirements [13, 14, 15, 16].

NIST is still involved in detector research. One project involves the development of an apparatus for evaluating the performance of multi-sensor devices. Called the Fire Emulator/Detector Evaluator (or FE/DE), the apparatus shows real promise for international standardization [17]. With links to the Indiana Dunes Tests, NIST is conducting a new evaluation of residential smoke detectors (now commonly referred to as smoke alarms). This work intends to re-examine the installation and siting rules, the efficacy of current sensor technologies, examine nuisance alarm sources, and develop data with which alarm algorithms might be developed for multi-sensor devices.

Finally, NIST is using its experience in computational fire models to develop a "sensor-driven" or "inverse" model [18]. Where traditional fire models start with the heat release rate of the fire and predict the fire's impact on the building this model takes the analog signal from fire sensors and predicts the heat release rate of the fire most likely to be producing those signals. This model holds promise in allowing fire alarm systems to produce real time data of significant use to the fire service in making tactical decisions, as well as evaluating detector signals for consistency with fire chemistry and physics and determining the level of threat to people and property.

Fire detectors and the systems to which they connect play a significant role in the reduction of fire losses. Thus the NIST fire program will continue to conduct research on detection as a means to achieve its goals of reducing the burden of fire.

The Department of Commerce recognized Richard Bright's work on smoke detectors with its award of the Silver Medal in 1976.

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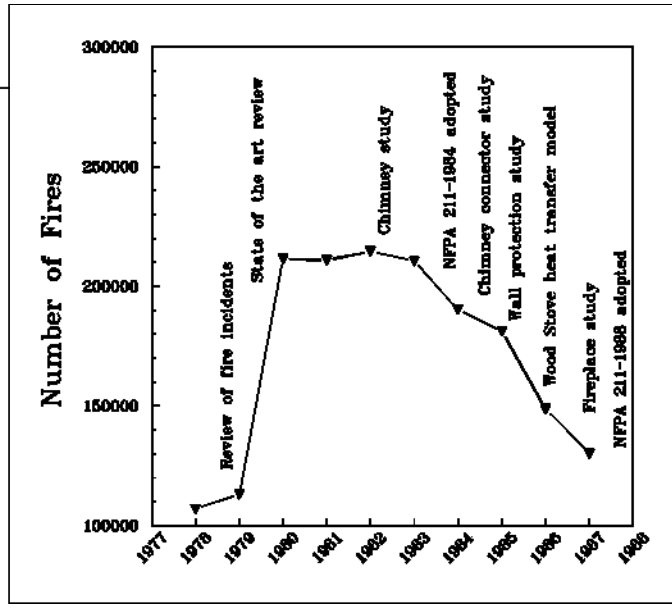
11.6 WOOD HEATING SAFETY RESEARCH

The energy crisis in the late 1970s led to a large increase in the use of wood as an alternate heating source. Along with this increase came a dramatic increase in the number of unwanted fires. The marked increase in the late 1970s and early 1980s is attributed to a growing number of installations and expanded use of wood burning stoves in homes throughout the United States and the fact that most homes are made of combustible construction. Standards for the safe installation and use of the appliances were based on information more than 40 years old and rarely applicable to modern appliances.



BFRL led concentrated research efforts to provide new and updated information to develop appropriate codes and standards for the modern appliances. Programs have been targeted to raise consumer awareness through education and to improve the standards and codes governing the construction, installation, and testing of appliances. Much of the supporting technical information for the standard and code changes and for consumer education has come from BFRL research. The point has finally been reached when much of the 40-year-old data and folklore originally used to develop the codes, standards, and public educational materials is being replaced by solid technical information.
Wood heating safety research at BFRL concentrated on several key aspects of the fire problem: clearances needed between wood burning appliances and combustible construction materials, creosote buildup and burnout, protective barriers to allow reduced clearances of appliances to combustible walls, safe methods of joining a chimney connector to a masonry chimney through a combustible wall, and theoretical prediction of appliance/wall heat transfer with arbitrary wall protection. As the research results became available in NIST reports and journal articles, BFRL staff worked closely with building and fire code committees to develop a new generation of code requirements for wood heating appliances. Most of the current codes related to wood heating are based on BFRL research.

Positive actions by BFRL and others have improved the safety of these appliances and, thus, reversed an increasing fire incidence rate. After several years of extensive research and activity in this area, new and up-to-date technical information and standards on fire safe installation and use of solid fuel heating appliances have contributed to reversing a dramatically increasing fire problem. A review of related publications are listed [1-6].

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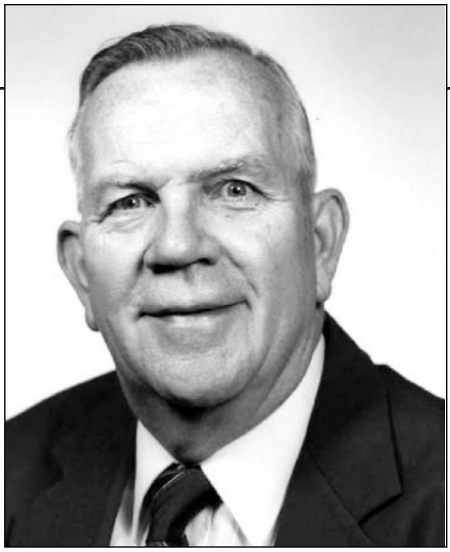
11.7 FIRE SAFETY EVALUATION SYSTEMS

The Fire Safety Evaluation System (FSES) was conceived of by Harold (Bud) Nelson and Irwin Benjamin to provide a series of separate systems each designed to measure the level of fire safety of an existing or proposed structure housing a given type of occupancy. These have provided means of meeting or exceeding the level of safety prescribed by the applicable code while providing the designer with a wide range of cost saving and functional options. The FSES for Health Care Facilities [1] was the first of a series of documents covering a variety of types of occupancies including apartment buildings [2], prisons and jails [3], office and laboratory buildings [4], overnight accommodations in National Parks [5], and board and care facilities [6].

The FSES for Health Care Facilities was part of a broad fire safety effort sponsored by the Department of Health and Human Service in response to an important need to develop a means of meeting the fire safety objectives of prescribed codes without necessarily being in explicit compliance with the code. In the 1960s with the birth of the Medicare and Medicaid programs Congress prescribed conformance with the requirements of the Life Safety Code, National Fire Protection Association Standard 101, in all nursing homes and hospitals receiving funds under the program. A nation-wide inspection and enforcement program was established to assure compliance. Most if not all inspected facilities were found to be in some degree of non-compliance with the specific requirements of the Life Safety Code. A significant number were closed as a result. Others undertook correction programs. Many, including some of the Nation's largest and most prestigious hospitals, were declared to fail this safety standard.

The FSES for Health Care Facilities was developed to discover alternate solutions, delivering at least an equivalent level of safety as compared to that produced by exact compliance with the detailed prescriptions of the Life Safety Code. In the case of one large hospital complex, the use of the FSES



Harold Nelson, innovative fire protection engineer.

reduced the cost of compliance from an estimated $30 million to $60 million to less than $2 million. Equally important, the development of alternative approaches allowed the improvements to be made without interruptions of hospital services.

The FSES is a grading system designed to determine the overall level of fire safety of an existing or proposed facility in comparison with a hypothetical facility that exactly matched each requirement of the Life Safety Code. The system is based on common building factors that determine fire safety, such as type of construction, partitioning and finishes, hazardous activities, fire detection and fire suppression and fire alarm systems. For practical considerations, however, factors relating to building utilities, furniture, and emergency procedures are handled elsewhere in the FSES. An informative discussion of the relevance of the approach to validity is available in Nelson's paper An Approach to Enhancing the Value of Profession Judgment in the Derivation of Performance Criteria [7].

The FSES for Health Care Facilities was adopted by the National Fire Protection Association as part of the 1981 edition of the Life Safety Code and a recognized means of developing alternative approaches to determine compliance with the code in that and later editions of the Life Safety Code. The FSES's have been adopted into building codes and similar regulations and have been institutionalized by the establishment of a special technical committee of the National Fire Protection Association (NFPA) charged with the responsibility for Alternative Methods for Life Safety in Buildings. This committee maintains NFPA Standard 101A [8] in support of the FSES's, thereby assuring that each FSES remains current and an appropriate reflection of the changing safety levels prescribed by building codes and regulations.

Subsequently, the Life Safety Code adopted FSES's developed by NBS/NIST covering Detention and Correctional Occupancies (i.e. prisons and jails), Board and Care Occupancies, and Office Occupancies. In 1995 the National Fire Protection Association created a new document NFPA 101A, Guide on Alternative Approaches to Life Safety [8] to gather and contain the FSES's in a single publication and place them in the care of a single technical committee. Nelson was the initial chair of this committee, and upon his retirement the chair was given to David Stroup, also of NIST.

The FSES for Board and Care Occupancies includes an innovative method for appraising the emergency evacuation capability of the occupants and staff of a board and care home housing persons of varying individual capacity and varying staffing. The system, developed under the leadership of Bernard Levin, measured the amount of assistance needed by each housed individual as compared to the capabilities of the staff to provide the needed help. The result was a break through in understanding the life safety needs of group homes housing persons of diminished capabilities.

The FSES's have stood the test of time and are now a regular part of life safety design in many buildings. They have both improved safety and reduced costs. In the NIST study Benefits and Costs of Research: A Case Study of the Fire Safety Evaluation System by Chapman and Weber [9], an estimate savings of almost $1 billion up to 1995 was credited to the FSES for Health Care Facilities. Unmeasured but significant savings have also been achieved by the other FSES's.

In the early 1980s Chapman and his colleagues [10] extended the work of Nelson's team by the development of a cost optimizer computer program enabling the user to determine the best cost acceptable alternatives to achieving equivalent safety with the Life Safety Code requirements for Health Care Facilities. In 1994 this work was used to develop the computer program ALARM 1.0, Decision Support Software for Cost-Effective Compliance with Fire Safety Codes [11].

In the long term, the principal importance of the fire safety evaluation systems lies not only in the specific objectives of delivering safety with lower cost and greater design flexibility, but in the demonstration that a total performance approach to fire safety was feasible. Nelson's contributions to FSES and other fire safety technologies have been recognized by Silver and Gold Medal Awards from the U.S. Department of Commerce, in 1982 and 1989 respectively, the Special Award for Technology Transfer of the Federal Research Laboratory Consortium, the first Harold E. Nelson Professional Service Award from the Society of Fire Protection Engineers, the Standards Medal of the National Fire Protection Association, and the Kawaoe Medal of the International Association for Fire Safety Science. In addition, Irwin Benjamin received the Department of Commerce Silver Medal in 1979 for his contributions to FSES

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11.8 SMOKE MANAGEMENT

Smoke management provides protection from smoke exposure by one or more of the following mechanisms: compartmentation, dilution, pressurization, airflow and buoyancy. From the early 1970s to the 1990s the objective of the NIST smoke management effort was to aid the advancement of this technology as it became an established part of building fire protection. This went beyond development of models to include concept studies, field tests, and large scale fire experiments. Thomas Lee received the Bronze Medal Award of the Department of Commerce in 1979 for development of the Smoke Chamber test method.

The 1983 book by ASHRAE, Design of Smoke Control Systems for Buildings [1], was primarily written at NIST and for the first time provided designers with methods of analysis for smoke control systems. John Klote and Harold Nelson of NIST were major contributors to the 1988 NFPA publication, Recommended Practice for Smoke Control Systems [2] that incorporated the approaches of the 1983 book. These approaches were based on engineering principles, and they were experimentally verified by large scale fires at the Plaza Hotel in Washington, DC [3].

Smoke protection of large spaces such as atria are a unique challenge, and John Klote and Harold Nelson were major participants in the development of 1991 NFPA standard, Guide for Smoke Management Systems in Malls, Atria, and Large Areas [4]. This topic was included in a more exhaustive book, Design of Smoke Management Systems [5] that was jointly published by ASHRAE and SFPE. Even before publication, John Klote won the 1991 BFRL Communication Award for his work on this book. Four ASHRAE best paper awards won by John Klote [3, 6, 7, 8] are an indication of the quality of NIST work in this area.

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11.9 SOFTWARE FOR FIRE HAZARD ASSESSMENT

NIST Handbook 146, HAZARD I - Fire Hazard Assessment Method [1], represents the culmination of a long-term program aimed at placing the prediction of fire outcomes on a more objective and scientific basis. In the 1970s NBS provided a grant to Harvard University to develop numerical models that could predict, from the basic equations of heat transfer and fluid flow, the temperature in a room containing a fire. These early models were difficult to use and interpret; required large, mainframe computers that were only available in academic institutions; and were plagued with long execution times often interrupted by software crashes. Major pieces of fire physics and most fire chemistry were not well enough understood to be included in the models, so that predictive accuracy was disappointing. As a result, these early models were little more than academic playthings, which were seldom put to practical use.

In 1983 CFR established a goal to develop a tool that could evaluate the role of the fire performance of an individual material or product in the outcome of a specific fire in a specific compartment or group of compartments. The first year of the effort was involved with determining what capabilities would be needed to accomplish this, and the result was somewhat daunting. Not only would it be necessary to predict the fire environment in the space resulting from the material or product burning, but it would also require understanding the movement and behavior of occupants and the physiological and psychological effects of exposure to this fire.

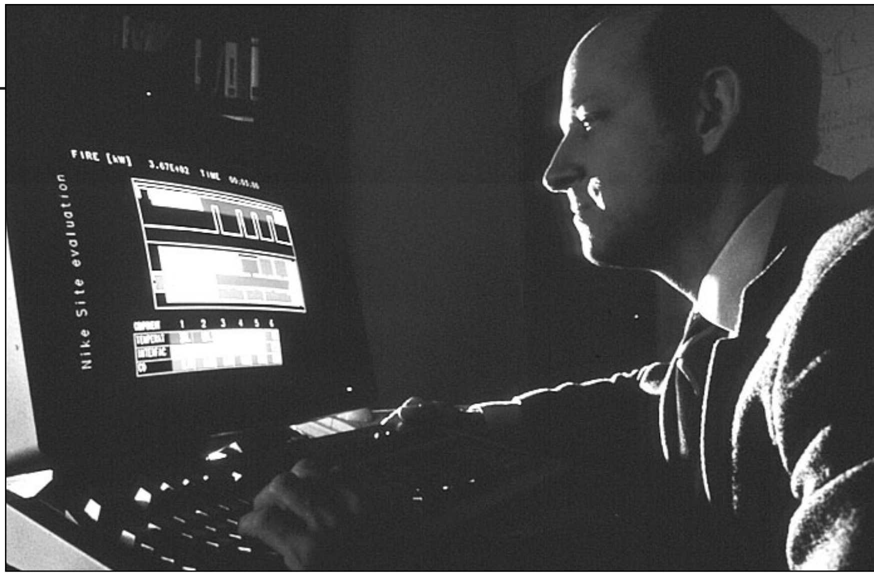
Since the project started before the personal computer revolution, the initial plan was to develop the software to run on NBS's mainframe and to equip a "fire simulation laboratory" at NBS with terminals and graphics equipment so that scientists and engineers could learn how to use the software to address practical problems. Once the usefulness of these models were appreciated, the larger engineering firms were expected to invest in the hardware needed to exploit the technology. Somewhere by the end of the century these firms would have the computers to run the software in their own offices.

By 1986 the CFR multi-compartment model, FAST (Fire and Smoke Transport) [2] had been enhanced so that its predictions were credible when applied within specific bounds. CFR's pioneering development of oxygen consumption calorimetry provided a means to measure the rate at which mass and energy were released from a burning item. By expressing a material's fire performance in terms of conserved quantities, it was possible to describe burning behavior for a predictive model. An CBT psychologist was developing a unique evacuation model with embedded behavioral rules derived from interviews with fire victims. Finally, the CFR combustion toxicology program was producing data that showed toxicological effects were primarily from a small number of toxic species.

Also at this time, the personal computer revolution was well underway. It became clear that a computer on every desktop would soon be a reality, so the CFR software was now targeted at that audience. Efforts were expended on an improved user interface that would both simplify data entry at the front end and provide graphical output support to make the results more understandable and useful at the back end.

In 1989 the first version of the HAZARD I software and documentation [1] was released. The software was designed to provide material and product manufacturers with a tool to assess the fire hazards of their products and a means to justify higher costs associated with better performing products. However, the manufacturers were underwhelmed because the methods required some skill to apply and were unproved.

Several pressures came together to begin to change perceptions of the potential of HAZARD I. First, there was political pressure to regulate combustion toxicity, with one state actually promulgating a regulation. NIST produced a fire hazard analysis that showed burning rate was much more important as an indicator of fire hazard than toxicity. Second, a well respected fire protection engineer became inter-



The Hazard I computer model was developed for engineers, architects, building owners, and others to predict the spread of smoke, toxic gases, and heat from a fire in a room to other parts of a building without having to burn a room or building. This photo shows one of the developers, Walter Jones, physicist, running the fire model from this software suite.

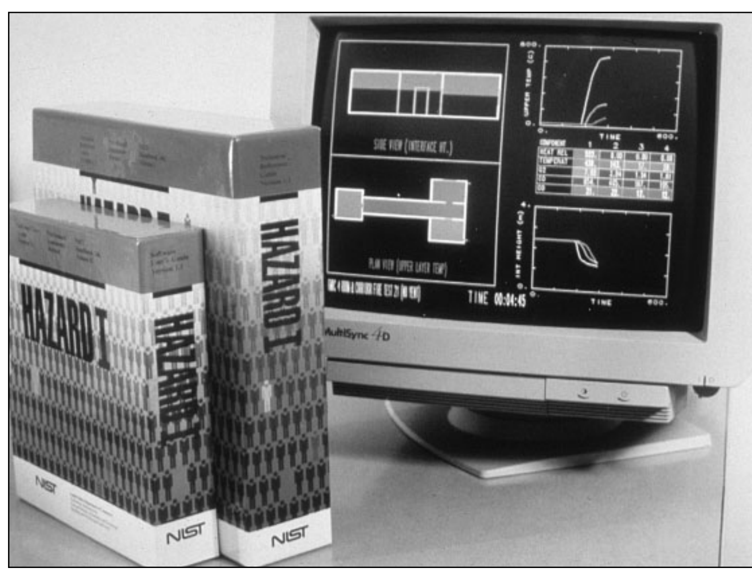
ested in learning these new techniques and successfully applied HAZARD I to absolve clients of liability in civil litigation involving a fire. This led to additional uses in both civil and criminal litigation and represented the first significant application of modern fire models.

The publication of NIST Handbook 146 represented a watershed for NIST in several ways. While NIST had developed and distributed other software products (such as DATAPLOT, a scientific graphing package), HAZARD I was an engineering analysis tool that could be used to make (literally) life and death decisions. It contained a broad range of engineering and scientific methodology that needed to be appropriately documented. Documentation consisted of a Technical Reference Guide, which underpinned the equations and assumptions and explained how they are coded, a set of worked examples, and a Users' Guide to the software. The product was packaged as a commercial product with printed binders for the manuals, shrink wrapped disks with the software and installation program, and even a printed function key template. This Handbook received special scrutiny on technical, policy, and legal fronts and was the model for most NIST software to follow.

The HAZARD I product was distributed under a formal agreement with the National Fire Protection Association (NFPA), a not-for-profit standards organization. They offered for purchase an initial package, upgrades when issued by NIST, and discounts for their members. Over a decade they sold several thousand copies.

One interesting aspect of this development involved the exclusion of government-developed software from copyright. Since the software is in the public domain, users are legally unencumbered by the cautions in the documentation. A solution was found in including a users' registration card that is to be signed, dated, and returned to qualify for technical support. The signature on the card was below a statement that the signer read and agreed to the limitations in the documentation - thus creating a contractual agreement. Later, a Government Accounting Office study of the copyright policy applied to government software cited two specific examples of critical government software that should have

HAZARD I software and documentation package. In 1989, the first version of the HAZARD I software and documentation (NIST Handbook 146) was released. HAZARD I includes several technological advances that were crucial to its acceptance in practice: the CFAST fire model, the EXITT evacuation model and the TENAB toxicology model. This is the only existing software suite to provide a complete hazard analysis for unwanted fires.



copyright protection - Grateful Med from the National Library of Medicine and HAZARD I. Several legislative proposals on this issue were considered but never adopted.

By 1990 successes in litigation led the fire protection engineering community to begin to use HAZARD I in building design. While building codes prescribed the minimum required fire safety features of buildings, they also contained a provision recognizing alternate approaches that can be shown to provide equivalent protection. Demonstrating this equivalence to regulatory authorities was always the difficult part. Now HAZARD I could be used to show equivalence in safety to occupants rather than having to prove that an alternative approach performed the same function.

The acceptance of HAZARD I in demonstrating code equivalence led to a global revolution in building codes. It became possible for codes to specify only the desired outcomes in terms of life safety and property protection and to allow any solutions that provided that level of performance. Such performance-based codes had long been discussed but were impractical until means were available to measure fire safety performance quantitatively. The U.S. building regulatory community began work in 1996 on a performance code, which was published in 2000. As similar codes are being developed and adopted in other countries these are eliminating non-tariff barriers to trade that result from unique, local or country-specific, test methods. These are being replaced by nearly uniform performance objectives. HAZARD I and its sub models are specifically cited in most of these codes and supporting guidelines documents as an acceptable means of demonstrating compliance with the codes.

HAZARD I included several technological advances that were crucial to its acceptance in practice. First, the fire model, FAST, was more robust and easier to use because of a significant investment in the user interface software. There were embedded databases of material properties, and additional references to data were cited. One of the criteria used by the development team was to require as inputs only data that were available and to cite sources for everything. Many other models at the time used engineering estimates that required coefficients to be entered by the user based solely on judgment rather than properties for which measurement methods and handbook values existed.

The equation solver used was carefully selected to work efficiently and seldom failed to converge. The software could be run interactively (with real-time graphics) for exploratory purposes or in batch mode to generate case files or for sensitivity analysis in engineering applications.

The FAST model predictions were compared to a range of full-scale experimental data and these comparisons were published to form a body of verification literature. Further, a suite of test cases was developed that stressed the model in different ways to see if it would fail. This test suite was run each time the model was modified. Computer Aided Software Engineering (CASE) tools were used to document changes to the model and to allow changes to be reversed if necessary. Each revision of the software was backward compatible so that users would not have to work excessively to re-run older cases, and the effect of changes was documented. Each of these aspects followed good (commercial) software development practice.

The EXITT (for Exit Time) [3] evacuation model differed from most of its contemporaries in the inclusion of a behavioral sub model. Other evacuation models of the day had everyone making the correct decisions and, while some allowed for user-selected decision delays, people marched quickly toward the exits. In HAZARD I people investigated the fire until seeing smoke or flame, assisted other family members, or even (children) hid or waited for instructions from an adult. The result was an amazingly realistic sequence of actions and an evacuation process that convinced users and authorities of its applicability.

The toxicology module TENAB (for Tenability) [1] was the only 20th century attempt to model physiological effects of the inhalation of a mixture of toxic gases. Based on correlations to data from animal exposures, but with an implementation that mimics important physiological interactions, the model produced results that aligned well to actual fire experience. In one case, HAZARD I successfully predicted the development of the fire, including a prediction of which occupants successfully escaped and which died, including the location of the bodies and the autopsy results on each. This particular case involved NIST using HAZARD I to support a Justice Department attorney to defend the federal government in a wrongful death suit from a fire on a military base. The final analysis indicated no fault by the government, and the day following the deposition of the NIST staff the plaintiff's council offered to settle this $26.5 million suit for $180 thousand.

NIST's pioneering work to develop engineering tools to predict fire performance in buildings, and especially the HAZARD I methodology, represented the enabling technology for the move to performance-based building and fire codes which are being adopted globally. The methods and models included in HAZARD I are routinely cited in these performance-based codes and in their associated codes of practice, worldwide. These performance methods are reducing the costs of fire safety in the built environment and are eliminating non-tariff barriers to trade for U.S. companies. Emil Braun, Richard Bukowski, Lynn Forney, Walter Jones, and Richard Peacock received the Silver Medal Award of the Department of Commerce in 1990 for the development of HAZARD I.

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11.10 LARGE EDDY SIMULATIONS OF FIRES

11.10.1 INTRODUCTION

The idea that the dynamics of a fire might be studied using digital computers probably dates back to the beginnings of the computer age. The concept that a fire requires the mixing of a combustible gas with enough air at elevated temperatures is well known to anyone involved with fire. Graduate students enrolled in courses in fluid mechanics, heat transfer, and combustion have been taught the equations that need to be solved for at least as long as computers have been around. What is the problem? The difficulties revolve about three issues: First, there are an enormous number of possible fire scenarios to consider. Second, there is neither the physical insight nor the computing power to perform all the necessary calculations for most fire scenarios. Finally, since the "fuel" in most fires was never intended as such, the data needed to characterize both the fuel and the fire environment may not be available.

Howard Baum of CFR and Ronald Rehm, then of the Center for Applied Mathematics, tackled the problem in one of NBS Director Ambler's first "competence" projects. The results show the wisdom of his decision to invest in fundamental, path-breaking research to place NBS in a lead position in the most important areas of science and technology.
In order to make progress, they greatly simplified the problem. Instead of seeking a methodology that can be applied to all fire problems, they began by looking at a few scenarios that were most amenable to analysis. They used idealized descriptions of fires, based on the kind of incomplete knowledge of fire scenarios that is characteristic of real fires, and approximate solutions to the idealized equations. However, the methods were capable of systematic improvement as physical insight and computing power grew more powerful.

The "Large Eddy Simulation" (LES) technique, developed at NIST over a nearly two decade period, refers to the description of turbulent mixing of the gaseous fuel and combustion products with the local atmosphere surrounding the fire. This process, which determines the burning rate in most fires and controls the spread of smoke and hot gases, is extremely difficult to predict accurate-

Howard Baum pioneer of the new generation of fire models.

ly. This is true not only in fire research but in almost all phenomena involving turbulent fluid motion. The basic idea behind the use of the LES technique is that the eddies that account for most of the mixing are large enough to be calculated with reasonable accuracy from the equations of fluid mechanics. The hope (which ultimately was justified by appeal to experiments) was that small-scale eddy motion can either be crudely accounted for or ignored.

Ronald Rehm, co-developer of large eddy simulations of fire phenomena.

The equations describing the transport of mass, momentum, and energy by the fire induced flows were simplified so that they could be solved efficiently for the fire scenarios of actual interest. The general equations of fluid mechanics describe a rich variety of physical processes, many of which have nothing to do with fires. Retaining this generality would lead to an enormously complex computational task that would shed very little additional insight on fire dynamics. The simplified equations, developed by Rehm and Baum [1], have been widely adopted by the larger combustion research community, where they are referred to as the "low Mach number" combustion equations. They describe the low speed motion of a gas driven by chemical heat release and buoyancy forces.

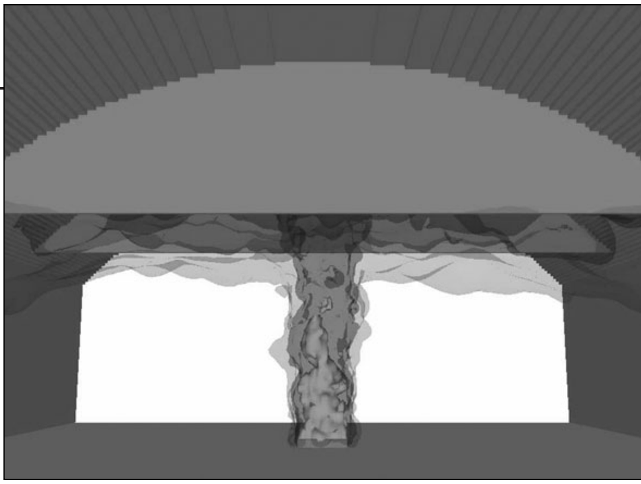
The low Mach number equations are solved on the computer by dividing the physical space where the fire is to be simulated into a large number of rectangular cells. In each cell the "state of motion," i.e. the gas velocity, temperature, etc. are assumed to be uniform; changing only with time. The computer then computes a large number of snapshots of the state of motion as it changes with time. The figure shows one such snapshot of a hangar fire simulation. Clearly, the accuracy with which the fire dynamics can be simulated depends on the number of cells that can be incorporated into the simulation. This number is ultimately limited by the computing power available to the user. Present day computers limit the number of such cells to at most a few million. This means that the ratio of largest to smallest eddy length scales that can be resolved by the computation (the "dynamic range" of the simulation) is roughly 100 to 200.

Unfortunately, the range of length scales that need to be accounted for if all relevant fire processes are to be simulated is roughly ten to one hundred thousand. Much of the discrepancy is due to the fact that the combustion processes that release the energy take place at length scales of 1 mm or less.

11.10.2 FIRE PLUMES

The idea that different physical phenomena occur at different length and time scales is central to an understanding of fire phenomena, and to the compromises that must be made in attempting to simulate them. The most important example is an isolated fire plume in a large well ventilated enclosure.

Simulations of scenarios of this kind are reported in [2, 3]. The fire plume is the "pump" which entrains fresh air and mixes it with the gasified fuel emerging from the burning object. It then propels the combustion products through the rest of the enclosure. The eddies that dominate the mixing have diameters that are roughly comparable to the local diameter of the fire plume. Thus, in the above simulation, the cells have to be so small that many (a 12 x 12 array in this case) are used to



Simulation of a fire in a hanger.

describe the state of motion across the surface of the fuel bed. Since the simulation also needs to include the remainder of the hangar as well, even the 3 million cell simulation shown above cannot cope with the combustion processes without additional modeling effort.

Physical processes like combustion that occur on scales much smaller than the individual cell size are often called "sub-grid scale" phenomena. The most important of these for our purposes are the release of energy into the gas, the emission of thermal radiation, and the generation of soot together with other combustion products. These phenomena are represented by introducing the concept of a "thermal element" [4]. This can be thought of a small parcel of gasified fuel interacting with its environment.

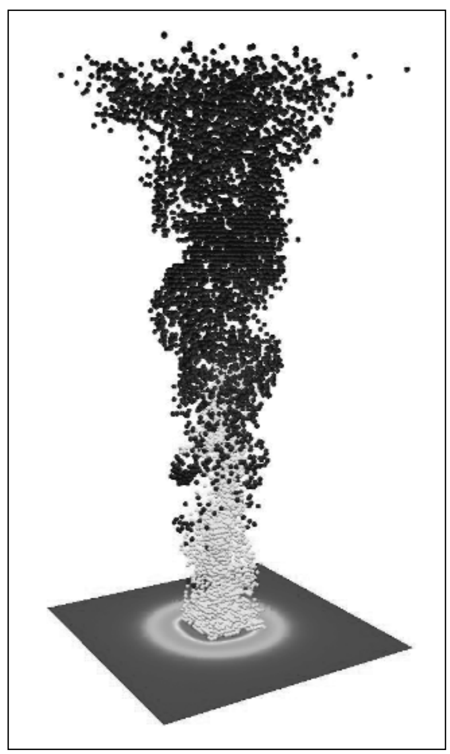
Each element is carried along by the large scale flow calculated as outlined above. As long as the fire is well ventilated, it burns at a rate determined by the amount of fuel represented by the parcel and a lifetime determined by the overall size of the fire. The lifetime of the burning element is determined from experimental correlations of flame height developed by McCaffrey [5]. A prescribed fraction of the fuel is converted to soot as it burns. Each element also emits a prescribed fraction of the chemical energy released by combustion as thermal radiation. This fraction is typically about 35 percent of the total. The soot generated by the fire can act as an absorber of the radiant energy. Thus, if the fire generates large amounts of soot, the transport of radiant energy through the gas must be calculated in detail [6]. Even in the absence of significant absorption of radiant energy by the products of combustion, the radiant heat transfer to boundaries is an important component of the total heat transfer to any solid surface.

11.10.3 OUTDOOR FIRES

Large outdoor fires can be conveniently divided into two categories based on the fuel source. Wildland fires are characterized by a relatively low heat release rate per unit area of ground covered by fuel, but a very large area over which the fire can spread. Indeed, the description of the fire spread process is an essential part of any successful simulation of such an event. Industrial fires, in contrast, are usually much more highly localized but intense emitters of heat, smoke, and other combustion products. This is particularly true if the fuel is a petroleum based substance, with a high energy density and sooting potential. This latter type of fire is the object of study here.

The hazards associated with such fires occur on two widely separated length scales. Near the fire, over distances comparable to the flame length, the radiant energy flux can be sufficiently high to threaten both the structural integrity of neighboring buildings, and the physical safety of firefighters and plant personnel. At much greater distances, typically several times the plume stabilization height in the atmosphere, the smoke and gaseous

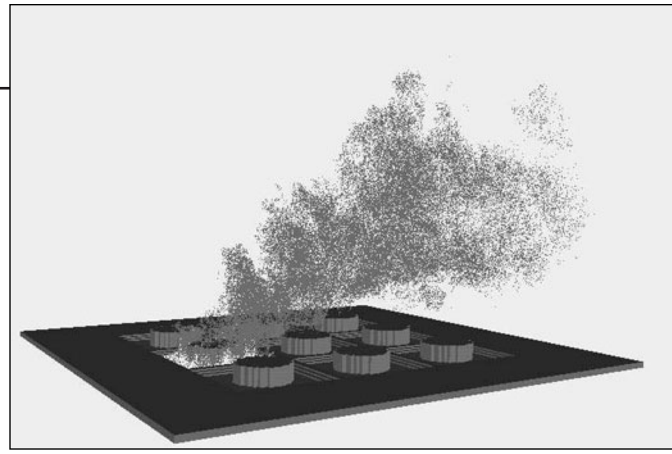
Thermal elements in a fire plume simulation of hot and burned out thermal elements; net reflective flux on the floor.



products generated by the fire can reach the ground in concentrations that may be unacceptable for environmental reasons. This latter, far field, hazard has been studied extensively by NIST researchers [7, 8]. This work has led to the development of a computer code ALOFT [9] and its generalizations to complex terrain.

A distinct approach is needed to model the near field hazard associated with the flame radiation. An example scenario is a fire surrounding an oil storage tank adjacent to several neighboring tanks. The heat release generated by a fire on this scale can reach several gigawatts if the entire pool surface is exposed and burning. Such fires interact strongly with the local topography (both natural and man made), and the vertical distribution of wind and temperature in the atmosphere. Moreover, the phenomena are inherently time dependent and involve a wide temperature range. Thus, the simplifications employed in ALOFT and its generalizations can not be used, and the "low Mach number" combustion equations need to be modified to account for the stratification of the atmosphere.

The photograph shows a simulation of a fire resulting from an oil spill trapped in the containment trench surrounding one of a number of oil tanks [10]. The diameter of each tank is 84 m, the height 27 m. A wind profile that increased from 6 m/s near the tank top to 12 m/s at 768 m that is representative of the atmospheric mean wind profile near the ground was chosen. The ambient temperature was taken to be constant. This is a very stable atmosphere, typical of winter conditions in northern climates. The spilled oil in the trench was assumed to burn with a heat release rate of 1,000 kW per square meter, for a total heat release rate of 12.1 GW. Each element was assumed to emit 35 percent of its energy as thermal radiation, and 12 percent of the fuel was converted to soot.



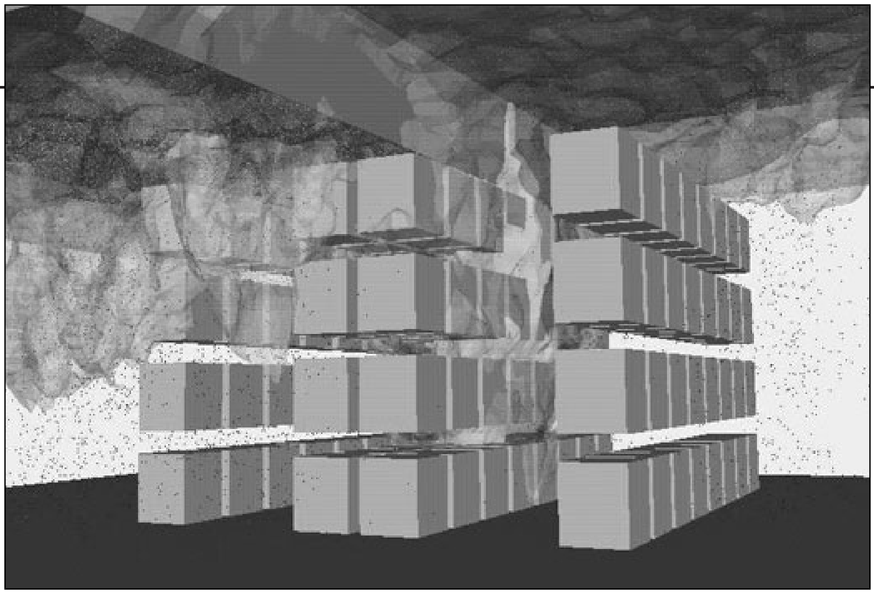
Large Eddy Simulation of a fire in containment trench surrounding an oil storage tank.

The bright colored elements in fig. (oilplume) are burning, releasing energy into the gas and the radiation field. Thus, the composite burning elements represent the instantaneous flame structure at the resolution limit of the simulation. The dark colored elements are burnt out. They represent the smoke and gaseous combustion products that absorb the radiant energy from the flames. It is important to understand how much of the emitted radiant energy is re-absorbed by the surrounding smoke. The model showed that of the original 35 percent of the energy released as thermal radiation, 29 percent was reabsorbed, in agreement with earlier measurements by Koseki [11].

11.10.4 INDUSTRIAL FIRE CONTROL

Recently, the LES techniques have begun to be used to study the effects of human intervention to control the damage caused by fires. The International Fire Sprinkler, Smoke and Heat Vent, Draft Curtain Fire Test Project organized by the National Fire Protection Research Foundation brought together a group of industrial sponsors to support and plan a series of large scale tests to study the interaction of sprinklers, roof vents and draft curtains of the type found in large warehouses, manufacturing facilities, and warehouse-like retail stores. The tests were designed to address relatively large, open-area buildings with flat ceilings, sprinkler systems, and roof venting, with and without draft curtains. The most elaborate tests involved a series of five high rack storage commodity burns.

In parallel with the large scale tests, a program was conducted at NIST to develop a computer model based on the LES methodology, the Industrial Fire Simulator (IFS) that incorporated the physical phenomena needed to describe the experiments. A series of bench scale experiments was conducted at NIST to develop necessary input data for the model. These experiments generated data describing the burning rate and flame spread behavior of the



Computer simulation of a rack storage cartooned plastic commodity fire test using the NIST Large Eddy Simulated Fire Model.

cartoned plastic commodity, thermal response parameters and spray pattern of the sprinkler, and the effect of the water spray on the commodity selected for the tests.

Simulations were first compared with heptane spray burner tests, where they were shown to be in good quantitative agreement with measured sprinkler activation times and near-ceiling gas temperature rise. The sprinkler activation times were predicted to within 15 percent of the experimental values for the first ring of sprinklers surrounding the fire, and 25 percent for the second. The gas temperatures near the ceiling were predicted to within 15 percent. Next, simulations were performed and compared with the unsprinklered calorimetry burns of the cartoned plastic commodity. The heat release rates were predicted to within about 20 percent. Simulations of the five cartoned plastic commodity fire tests were then performed see photograph.

The goal of these simulations was to be able to differentiate between those experiments that activated a large number of sprinklers and those that did not. This goal has been met. The model was also used to provide valuable insight into what occurred in the experiments, and what would have occurred for various changes of test parameters. Further information about this work can be found in [12,13].

There are plans to continue the development of the IFS model in the future. Much more work is needed to verify the additional models used to account for the flame spread, the interaction of the spray with fuel surfaces, and the various heat transfer mechanisms. However, the results obtained to date are certainly encouraging. The simulations yield information that is difficult if not impossible to obtain any other way. Moreover, it is possible to test the various assumptions and models individually against experiments designed to yield much more precise information than can be obtained from large scale tests. Thus, the knowledge gained from a limited number of large scale tests could be systematically extended by coupling this information to the results of computer simulations.

11.10.5 ACKNOWLEDGMENTS

The work described here is the contribution of many people at NIST. Howard Baum and Ronald Rehm collaborated over many years to develop these fire modeling capabilities. Kevin McGrattan has been the architect and creator of the computer programs that convert the simplified physical and mathematical models into practically useful predictive tools. William Mell and William Walton contributed their expertise to the modeling and experimental confirmations. Finally, the work was guided and encouraged over the years by the Late Professor Howard W. Emmons, who was the father of modern fire science. This section is based on a paper by Baum [14].

The Department of Commerce recognized fire modeling advances with a number of its medal awards.

- James Quintiere received the Bronze Medal in 1976 for studies of room fire growth.
- John Rockett received the Silver Medal in 1977 for early work in fire modeling.
- James Quintiere received the Silver Medal in 1982 for fire growth modeling.
- Bernard McCaffrey received the Bronze Medal in 1983 for large plume experiments and theory.
- Howard Baum and Ronald Rehm received the Gold Medal in 1985

for development of the large eddy simulation technique.

- Daniel Madrzykowski received the Bronze Medal in 2001 for large scale field fire tests.
- Kevin McGrattan and Glenn Forney received the Silver Medal in 2001 for advanced fire dynamics simulations.

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11.11 FIRE FIGHTER EQUIPMENT

11.11.1 FIRE DEPARTMENT GROUND LADDERS

During the decade of the 1960s several serious fire service accidents occurred when using ground ladders. The ladders failed during normal fire fighting operations. Some of the failures related to load carrying capabilities, and others failed as a result of loads and heating from the fire. The objective of this effort was to review existing standards to identify issues related to ladder failure, study key performance requirements for the use of fire service ground ladders, and recommend improvements for NFPA and American National Standards Institute (ANSI) ground ladder standards [1].

NBS' Fire Service Section of the Fire Technology Division teamed with the Prince Georges County, Maryland and Bowie, Maryland fire departments; and the Fire Service Extension Department of the University of Maryland to identify performance issues associated with the use of fire department ground ladders. Field studies of ground ladder applications were carried out. Metallurgical studies were conducted on three ladders that failed in service. Ladders were also tested for deflection response to load, failure in horizontal bending, and resistance to impact. Human factor issues related to sizing and design were studied. Information gained from these studies was presented to

ANSI and NFPA to assist in improving ground ladders standards.

Results from this study were presented to NFPA and ANSI. NFPA 193, Standard on Fire Department Ladders and ANSI A14.2 Standard for Portable Metal Ladders were both modified to reflect many of the recommendations made by NBS.

Participants in this project from NBS included H. P. Utech, T. Robert Shavers, Donald C. Robinson, Donald B. Novotny, Henry C. Warfield, and Joseph M. McDonagh. William E. Clark of the Prince Georges County, Maryland Department of Fire Protection also assisted with this study.

11.11.2 FIRE FIGHTERS' TURNOUT COATS

The purpose of this research was to improve the protection afforded fire fighters by their turnout coats and to insure the durability of the coats. It developed standard specifications for the selection and purchase of for fire fighters' turnout coats, and turnout coat specifications for development of a standard for fire fighters' protective clothing.

NBS conducted a series of studies to determine what was needed by the Fire Service in the use of turnout coats, and investigated the most practical means for meeting those needs [2]. The studies concentrated on evaluating what was available in the marketplace. Based on these studies and the needs and desires of the Fire Department of Prince Georges County, Maryland, a purchase specification was developed which was used by that county to purchase a number of coats. A coat manufacturer produced the coats, and the Prince Georges County Fire Department evaluated the garments through field use. Comments were obtained from the fire department, each Director of State Fire Service Training, the International Association of Fire Fighters (IAFF), turnout coat and coat component manufacturers, and other interested parties. The comments were analyzed and a new draft specification was prepared. The proposed changes were discussed at a series of seminars arranged by the fire service groups. Additional drafts of the specifications were prepared based on comments received, and a final report [3] was prepared.

Findings from this work were shared with the NFPA Sectional Committee on Protective Equipment for Fire Fighters that was a part of the Committee on Fire Department Equipment. The final NBS report was published in October of 1975 and NFPA adopted much of the report recommendations at its fall meeting on November 18, 1975. This standard, NFPA 1971, became the first American national standard for fire fighters' protective clothing.

Other organizations assisting with this project: Prince Georges County Maryland Fire Department; International Association of Fire Chiefs; International Association of Fire Fighters; International Fire Service Training Association; National Fire Protection Association; University of Maryland Extension Service; and the Federal Fire Council. This work was sponsored by the U.S.

Turnout coat damaged from thermal exposure.

Department of Commerce, National Fire Prevention and Control Administration.

11.11.3 FIRE FIGHTERS' PROTECTIVE CLOTHING

The initial project compared conditions measured in room fires conducted over several years at NBS' CFR to protection levels provided by fire fighter turnout coats and pants conforming with NFPA 1971, Standard for Protective Clothing for Structural Fire Fighting.

Heat flux conditions measured in seven room fire tests [4, 5] were compared to heat flux values and the thermal protective performance (TPP) ratings of fire fighters protective clothing. NFPA 1971 required that fire fighters' protective clothing protect the wearer against second degree burns when a heat flux of 84 kW/m^2 is applied to its outside surface for a minimum of 17.5 seconds. Heat flux data representing the TPP test exposures were superimposed on heat flux plots from the room fires.

Comparisons of heat flux from room fires to heat flux exposures from the TPP test showed that room fire will often exceed test conditions provided by the TPP test. Data from this study suggested that turnout garments that meet requirements for the NFPA 1971 TPP test only allow a short time for escape. Estimates for escape time from this study indicate that a fire fighter has less than 10 seconds to escape a flashover fire instead of the 17.5 seconds suggested by the NFPA TPP test.

The paper by Krasny, Rockett, and Huang received the Fire Technology, National Fire Protection Research Foundation, Harry C. Bigglestone Award For Excellence in Written Communication.

Example of modern fire fighter protective clothing under simulated thermal environment.

Although significant advances had been made in the performance of fire fighters' protective clothing, by the mid 1990s the number of serious burn injuries had remained constant for more than a decade. Therefore research was resumed to develop measurement methods and computer based predictive methods that would provide a detailed understanding of thermal performance for fire fighters' protective clothing. These analytical tools were designed to assist manufacturers in product development, assist the standards writing organizations in development of technically sound standards for thermal protective clothing, and provide the fire service with information and tools for selecting thermal protective clothing, training fire service personnel in the proper use of the protective clothing, and for analyzing fire fighter thermal injury cases.

An initial study [6] was conducted to quantify what was known about the thermal environments of fire fighting and fire fighter burn injury and death statistics. NIST rejoined the NFPA and ASTM technical committees that maintain standards on fire fighters protective clothing. A workshop [7] was held to identify fire service and protective clothing industry concerns associated with protecting fire fighters from thermal exposures and to facilitate the exchange of ideas. NIST worked with numerous fire departments to better understand issues related to the performance of fire fighters protective clothing. This effort included the study of serious burn injury cases and fire fighter fatality cases that resulted from thermal exposure. Existing ASTM and NFPA thermal test methods for measuring the thermal performance of fire fighters' protective clothing were evaluated [8]. Knowledge learned from these studies was carried to the laboratory and resulted in the development of two new thermal test apparatus [9, 10] that could be used to better quantify the thermal performance of fire fighters' protective clothing. In addition, an effort was begun to translate what was being learned from these studies into a physics based computer program for predicting the thermal performance of fire fighters' protective clothing. A one dimensional heat transfer model [11] was developed that could be used to predict heat transfer through the multiple layers of fire fighters' protective clothing garments. In addition, NIST developed thermal properties data [12] for the fire fighters' protective clothing predictive heat transfer model and began developing data on thermal conductivity. Other studies are underway to quantify specific heat and the thermo-optical properties of protective clothing materials.

Five major manufacturers of components for fire fighters' protective clothing and protective clothing garment systems have developed proprietary research agreements with NIST and have used the protective clothing thermal measurement facilities to study their products. Data generated by these measurement apparatus have resulted in design modifications to fire fighters' protective clothing and components used to fabricate fire fighters' protective clothing. Primary areas where protective clothing has seen improvements are turnout coat sleeve cuff designs, knee pad and elbow pad designs and improvements in thermal performance of trim materials.

Information on these measurement methods has been submitted to ASTM International Committee F23 on Protective Clothing and the National Fire Protection Association (NFPA) Committee on the Protective Ensemble for Structural Fire Fighting. Data from these measurement apparatus are being applied to performance evaluations of other test methods used for the analysis of thermal protective clothing.

Robert T. McCarthy, Chief, Fire Technical Programs Branch (USFA) worked with NIST in support of this effort. This project was supported by the U.S. Fire Administration (USFA) and the National Institute of Standards and Technology. Thomas Van Essen, Fire Commissioner, Chief Stephan J. King, Safety Chief, and Battalion Chief Hughie Hagan of the York City Fire Department (FDNY) supported development of the dynamic compression test apparatus, and Lt. Kevin S. Malley, Director of Human Performance (FDNY), became a NIST Guest Researcher to assist with development of the test apparatus and assisted with protective clothing testing and report preparation. Division Chief, Kirk Owen of the Plano, Texas Fire Department and Chairman of the NFPA Committee on the Protective Ensemble for Structural Fire Fighting provided technical council. The following fire departments participated in these efforts by cooperating with field studies and providing other forms of assistance: Austin Fire Department, TX; Cincinnati Fire Department, OH; Denver Fire Department, CO; Fairfax County Fire and Rescue Department, VA; Jacksonville Fire Department, FL; Lexington Fire and Emergency Services, KY; Louisville Fire Department, KY; Montgomery County Fire and Rescue, MD; York Beach Fire Department, ME. Manufacturers providing assistance and contributing materials for this research effort were: Alden Industries; Celanese Corporation, Dupont Advanced Fiber Systems; Globe Firefighter Suits; Lion Apparel Inc.; Minnesota Mining and Manufacturing Company (3M), Safety and Security Systems Division; Morning Pride Manufacturing, Inc.; Reflexite Corporation; Southern Mills Inc.; W. L. Gore and Associates. Other NIST staff participating in this effort were: Robert L. Vettori and Dan Madrzykowski.

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11.12 FIRE SPRINKLERS

11.12.1 INTRODUCTION

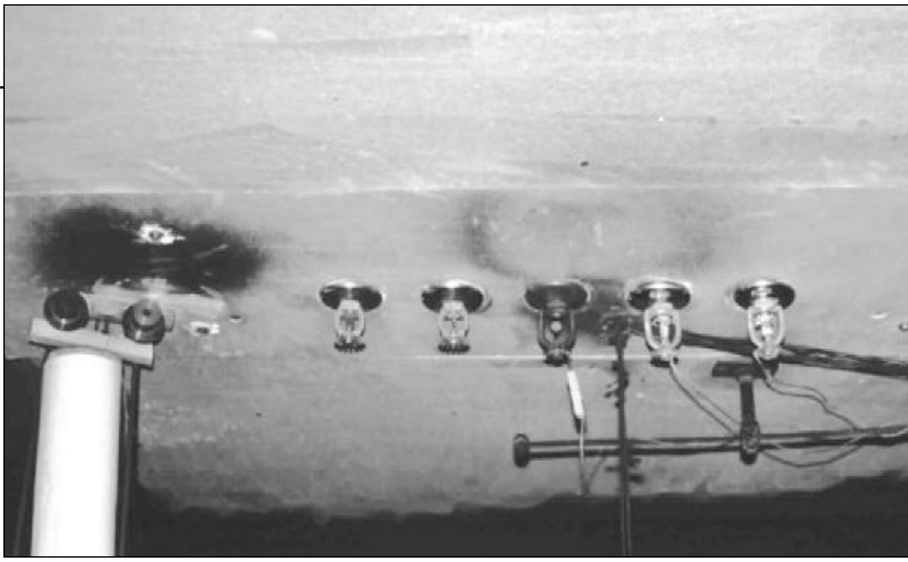
Automatic sprinkler systems have been successfully used to protect industrial and commercial buildings and their occupants for more than 100 years [1]. The Report of the National Commission on Fire Prevention and Control, America Burning, issued in 1973, changed the focus of sprinkler research, in both government and private sector labs, from protecting the building and its contents to protecting the occupants of the building [2]. The research efforts at NIST used measurements and analysis in order to develop methods of predicting automatic sprinkler response and fire suppression effectiveness. The impact of the research conducted during this period can be seen in a variety of engineering applications, standards development and as a foundation for much of the fire suppression research that is currently underway at NIST and other research laboratories around the world.

In its most basic form, an automatic fire sprinkler system consists of a water supply, piping to deliver the water from the supply to the sprinklers and thermally activated sprinklers. In most cases, each sprinkler has a temperature sensitive link. Hence water is only discharged in the area where the gases from the fire have gotten hot enough to activate the sprinkler. While the system seems simple enough, the process of accurately predicting multiple sprinkler activation and fire suppression from the water spray cannot be done a priori. As a result, the most reliable means of determining the effectiveness of fire sprinklers for a given set of conditions is full-scale testing.

11.12.2 FULL-SCALE FIRE SUPPRESSION EXPERIMENTS

By 1977, NBS had two major sprinkler research projects; 1) automatic sprinklers in health care facilities and 2) the use of sprinklers or water sprays for protection of open stairways [3]. These projects were being conducted by the Program for Fire Detection and Control in the Center for Fire Research (CFR).

New Sprinkler Technology for Health Care Occupancies– The objective of the first project, sponsored by the U.S. Department of Health, Education, and Welfare (HEW), was to determine the effectiveness of automatic sprinklers in terms of fire control and life safety. Over the course of this project, 1977 - 1982, O'Neill, Hayes and Zile conducted 21 full-scale fire experiments in a patient room, corridor and lobby arrangement that had been installed in a former NIKE missile base barracks building adjacent to the NIST Gaithersburg Campus [4, 5, 6]. The fires were set in mattresses with bedding or in wooden wardrobes filled



Instrumented "standard" and "quick" response sprinklers, installed in the Barracks Building at the NIST Annex (former Nike Site).

with clothing to demonstrate a "worst case" shielded fire. In later stages of the project, gas burners were used to replicate the thermal conditions of the burning furnishings [7].

The research was seminal in many ways, it demonstrated the life safety value of "fast response" (low thermal inertia) sprinkler activation technology. In addition, it provided a comparative database for temperatures, gas concentrations, and smoke obscuration based on the thermal response of the sprinkler, as well as the location of the sprinkler in the room i.e. pendent versus sidewall. Last but not least, the results of this research program were used to develop recommendations for the positioning of hospital privacy curtains with respect to the location of the sprinkler. Installation criteria based on the NBS recommendations were adopted in the National Fire Protection Association (NFPA) 13, Standard for the Installation of Sprinkler Systems, in 1983.

In 1993, the research on protecting patient rooms with sprinklers was augmented by Notarianni [8]. The research sponsored by the National Institutes of Health (NIH), focused on tenability conditions within the room of fire origin, with similar comparisons as the previous HEW sponsored studies, quick-response versus standard response sprinklers and pendent versus sidewall position. This work reaffirmed the utility of QR sprinklers for defend in place situations and provided further insight on the reduced level of obstruction created by privacy curtains with open mesh near the top.

Using Sprinklers to Limit the Spread of Fire and Smoke– O'Neill and Cooper studied the abilities of sprinkler and water spray nozzle systems to protect open stairways and other openings in fire-resistive walls and ceilings [9, 10]. The experiments, sponsored by the Occupational Safety and Health Administration (OSHA), were conducted in a three-story stairwell that was built in the opening of an underground bunker used for the storage of NIKE missiles. The stairwell was exposed to fire sizes up to 4 MW with and without the sprinklers. The results of the experiments demonstrated the effectiveness of sprinkler protection for openings and have provided data for use with NFPA 13.

Impact of Sprinklers on Office and Laboratory Fires– The next major series of full-scale sprinklered fire experiments began in the late eighties under the sponsorship of the General Services Administration (GSA). By now, NBS had developed oxygen consumption calorimetry methods, which had been implemented in the Large Fire Research Facility (Bldg 205). This enabled researchers to measure the impact of the sprinklers on suppressing the fire in terms of heat release rate. Walton conducted fire experiments examining the impact of sprinkler spray density on the burning fuels representing a "light hazard" [11]. The results demonstrated that 0.07 mm/s was the "reliable minimum" for rapidly reducing the heat release rate and suppressing the fire [11].

The GSA research was continued by Madrzykowski, with the objective of quantifying the sprinklered fire exposure on an exit corridor and spaces adjacent to that corridor [12]. The fire source in the burn room was a shielded wood crib, sized to maintain a 1 MW fire. Tenability was assessed using both temperature and gas toxicity criteria. The experiments showed that the sprinklers maintained tenable conditions in the corridor and in the adjacent room. Without the sprinkler protection, the corridor became untenable within 6 minutes.

GSA was funding this research as part of an effort to develop an engineering based approach to fire safety design [13]. Implementing this approach was constrained in part by a lack of relevant heat release rate data and the inability to determine the impact of an activated sprinkler. In response to this need, Madrzykowski and Vettori conducted a series of experiments burning a wide variety of office furnishings and measuring the heat release rate with and without sprinkler activation. The effect of a "light hazard" design density of 0.07 mm/s was documented and used as a basis for an empirical suppression model [14].

Under the sponsorship of GSA and NIH, Walton and Budnick conducted a set of fire sprinkler experiments in a lab building, which was slated for renovation, on the NIH campus [15, 16]. This test series is key for two reasons: first, it identified the life safety and design benefits of using quick response sprinklers in chemical laboratories and office areas and second, it was the first major fire research program conducted in a "field location." While the fire research program had conducted simple field experiments with simple instrumentation prior to NIH, this series of experiments included complex detection and suppression experiments and measurements. Several similar lab rooms were instrumented to record activation times of detection and suppression systems, temperature, and concentrations of oxygen, carbon dioxide and carbon monoxide. Videos of the fire room and hallway were made during the experiments. Walton would use this experience to optimize and enhance NIST's field measurement capabilities. In the decade that followed these capabilities would be used for a wide range of field experiments addressing mitigation of oil spills, fire suppression effectiveness of Class A foam, arson burn pattern studies and further studies on the impact of sprinklers in various occupancies.

11.12.3 SPRINKLER RESEARCH AREAS

Given the complexities of understanding sprinkler activation and suppression under actual fire conditions, the problem was de-coupled and studied in parts: activation, sprinkler spray characterization, cooling via water droplets, and suppression. Finally, several studies have been conducted looking at the potential impact of sprinkler systems.

Sprinkler Activation– The study of sprinkler activation at CFR was spearheaded by Evans [17, 18]. Beginning with the characterization of the thermal response of fusible links used to activate sprinklers, Evans' study of the thermal elements used in sprinklers and the characteristics of the hot gas environments generated by a variety of fires coupled with research conducted by Factory Mutual and others would soon lead to the development of a computerized means of predicting sprinkler activation [19-21]. In addition to laboratory-based experiments, many sprinkler activation experiments were conducted in "real world" environments including a mobile home, a hotel, and large aircraft hangers [22-27]. This data has been used to either evaluate a predictive sprinkler activation model or to develop new ones.

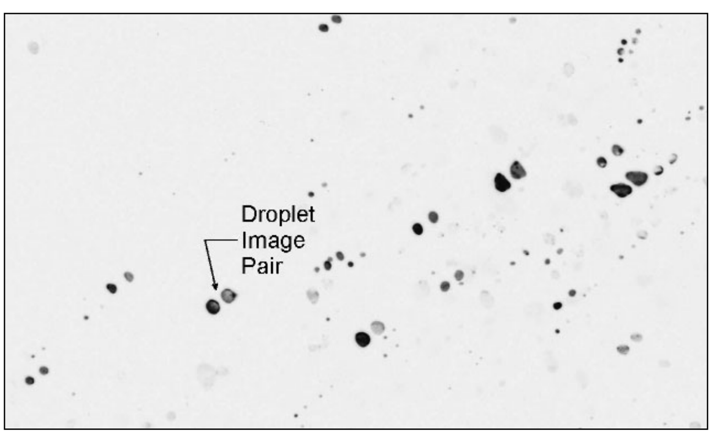
Sprinkler Spray Characterization– The measurement of sprinkler sprays has been addressed in a number of ways since 1985. The measurements have been limited by the measurement technology available at the time. Ideally a water droplet can be described in terms of size and velocity. This would enable the prediction of the trajectory of the droplet and the determination of the momentum of the droplet. Within the scope of a sprinkler spray, it is important to know the distribution of the droplet sizes and velocities in order to determine how this water spray may impact a fire.

Hayes conducted a literature survey of existing drop size data, means of measuring drop size and the significance of drop size in fire suppression [28]. His survey led to sprinkler spray measurements, sponsored by GSA and conducted by Lawson et al. using a computer controlled shadowgraph technique [29]. This device used a strobe light and light sensitive array to provide the measurements. Subsequently, spray measurements were conducted by Putorti et al. using an improved shadowgraph method incorporating a self contained laser beam and an optical diode array [30, 31]. In 2000, several researchers were developing water droplet measurements, Widmann using Phase Doppler Interferometry

Photographs (such as this) of sprinkler sprays were used to examine water sheet break-up and droplet formation in the 1980s.

(PDI) and Sheppard and Lueptow using Particle Image Velocimetry (PIV) [32]. While both methods permit accurate and non-intrusive measurements of sprinkler sprays, the PIV only measures mean drop velocity and does not provide drop size distribution, while PDI provides both drop size and velocity. Characterizing a sprinkler spray field is a tedious and difficult process given the small measurement volume used in both systems. As the new century dawns, Putorti and Atreya have begun the development of a unique measurement device, the large-scale planar laser, drop size and velocity measurement apparatus. After utilizing the best commercially available technology and falling short of the goal of fully characterizing the sprinkler spray it is hoped that this heuristic approach can provide the insight and the data required to enable a sprinkler spray based suppression predictive method.

Determination of water droplet size and velocity using the Particle Tracking Velocimetry and Imaging Technique (PTVI). Two images of each droplet are obtained by fluorescence with two laser sheets.



Photographs of water droplets fluoresced via a sheet of laser light. Computer analysis of this photo will provide droplet size and velocity data.

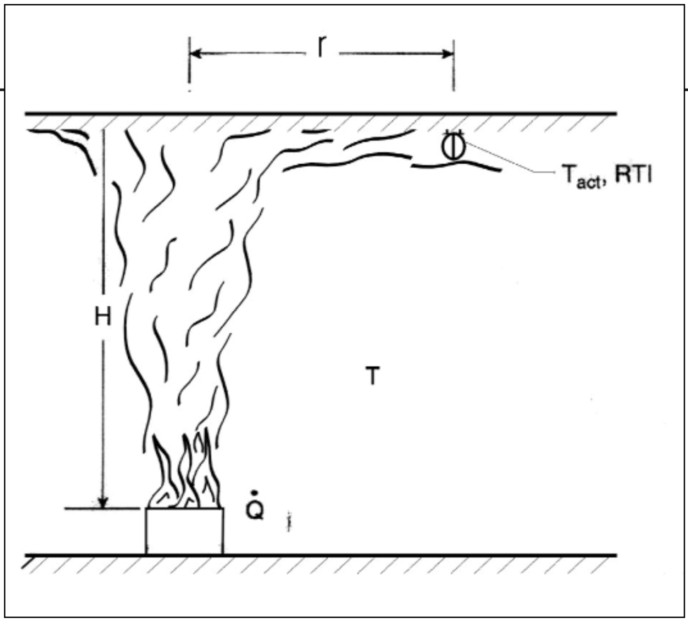
Sprinklered Fire Suppression - From 1986 through 1996, teams of University of Maryland students, led by diMarzo, with scientific oversight from Evans, have worked on measuring the cooling of a hot surface by droplet evaporation [33-38]. Based on the measurements, a coupled model was developed that can simultaneously yield the surface temperature and heat flux as well as the transient due to droplet evaporation. Coupled with the droplet measurements, the results from this research would provide a portion of the fuel-cooling piece of the fire suppression puzzle.

Given that the universal sprinkler suppression solution is still many years in the future, parallel research efforts were undertaken to provide a near term, although limited solution. The empirical suppression model by Madrzykowski and Vettori was incorporated in to FPETool [14, 39]. Based on these experimental results and those of Walton, Evans developed a generalized suppression model for light hazard occupancies that could account for a range of spray densities [40]. This model was incorporated into the HAZARD I model. As part of a National Fire Protection Research Foundation project on predicting the impact of sprinklers in high rack storage warehouses, Hamins and McGrattan embarked on a set of reduced scale experiments to develop a fire suppression model with a given fuel, (group A plastic commodity), in a given configuration, (rack storage), with a given water flux. Algorithms, compatible with a computational fluid dynamics model, describing the heat and mass transfer taking place during suppression were developed from the data [41].

Sprinklered Life Safety Analysis– In addition to studying the heat transfer and fluid dynamics aspects of sprinkler fire suppression, NIST has conducted studies focused on the life safety impact of installing sprinklers. In 1984, Budnick published a study estimating the improvement that state of the art detection and suppression technology could have on life safety in residential occupancies. It was estimated that residential sprinklers, in conjunction with a smoke detection/alarm system could reduce residential fire deaths by 73 percent [42]. Also in 1984, Ruegg and Fuller completed a cost benefit analysis on residential sprinkler systems [43]. In 1998, Notarianni and Fischbeck, developed a methodology to handle value judgments, such as the value of premature death avoided, by means of comparative analysis, parametric analyses, and switchover analysis. This methodology was applied to a model for determining the benefits and costs of residential fire sprinklers [44].

11.12.4 PREDICTIVE METHODS

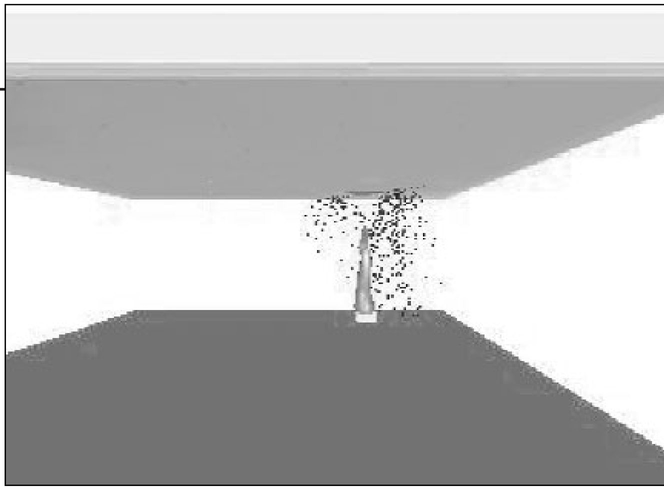
Stand Alone Sprinkler Activation Models– The predictive models of sprinkler activation and fire suppression are used by engineers around the world to address fire protection and investigation challenges. While these models are still under development, significant progress has been made by NIST fire research. In 1985, Evans and Stroup developed the first public domain computer model, DETACT-QS [45]. The model was designed for calculating the response time of heat detectors or sprinklers installed below large unobstructed ceilings. Stroup, Evans and Martin further developed another heat detector activation model, DETACT-T2, aimed at evaluating the response of existing systems with a range of fire growth rates [46, 47]. Given limited access to computers by the general engineering community, the models were published with a large number of cases pre-run and arranged in look-up tables. Two versions were published one in English units and one in metric units. Cooper, Stroup and Davis worked from 1986 through 1990 developing a different model for predicting sprinkler activation in a compartment [48-51]. The resulting model, LAVENT, considered the effects of a compartment, had the ability to accommodate vents in the ceiling and allowed the user to position the detector at different distances below the ceiling as opposed to DETACT which assumed that the detector was in the position of maximum temperature and velocity in the ceiling jet.



Schematic of DETACT-QS sprinkler activation model inputs.

Integrated Sprinkler Activation and Suppression Routines in Zone Models– As NIST continued to develop models that would consider fire development in the context of a room environment which could include heat loss to the walls and ceiling, doors or windows that could open and occupants, the basic DETACT sprinkler algorithm was incorporated [52-54]. Over the years refinements were added to the zone models' sprinkler capabilities, this included modifying the heat transfer algorithm to be more representative of actual compartment temperature conditions and adding limited empirical sprinkler suppression algorithms [39, 55]. However the zone models were still limited to the activation of the first sprinkler.

Multiple Sprinkler Activation with Suppression– Beginning in the mid 90s, McGrattan and Forney began examining the interaction of sprinkler sprays and fire gases using a computational fluid dynamics model (CFD) [56]. The CFD technology enabled the prediction of multiple sprinklers and how the water spray might inhibit the activation of additional sprinklers. At



Smokeview visualization of a heptane fire with two sprinklers activated.

this point, the model was known as the NIST Large Eddy Simulation (LES) fire model. NIST entered into an agreement with the National Fire Protection Research Foundation, where members of the foundation would fund full-scale fire experiments at UL's new state of the art test facility in Northbrook, IL. NIST would model the experiments and actually provide the model predictions before the experiments were conducted. McGrattan, Hamins and Stroup accepted the challenge of the International Sprinkler, Smoke and Heat Vent, Draft Curtain Fire Test Project for NIST [57. 58]. By the end of the project, 34 heptane spray burner experiments and 5 Group A plastic commodity high rack storage fires had been conducted. This did not include numerous reduced scale experiments to support model development. While the initial predictions for time to activation needed some improvement, the most challenging task of predicting the number of sprinklers to activate was met with great success. As other physical phenomena were incorporated into the model to improve the time to activation prediction, the model evolved and was renamed the Industrial Fire Simulator 2 (IFS2). McGrattan, Baum, Rehm, Hamins and Forney continued to improve the capabilities of the model and the first version of the NIST Fire Dynamics Simulator (FDS) was released in January of 2000 [59]. A sister model to FDS, Smokeview, was released in May [60]. This was a post processing scientific visualization tool, which allows the user to see the numerical results of FDS. Hence with Smokeview the user could watch the simulated fire develop in a room. Watch the sprinkler activate and suppress the fire, all on the screen of a computer monitor. This visualization model is one of the most dramatic improvements to the computer models because it enables a wider range of people, including: engineers, building owners, and other members of the fire protection community, to see and understand the results of an FDS model run.

11.12.5 SUMMARY

Since 1975, the fire research program at NIST has been leader in research aimed at developing and validating methods to predict the activation and suppression effectiveness of sprinklers. Results from this research have been incorporated into building codes and sprinkler standards. The sprinkler activation models are a critical piece of the infrastructure that supports performance based fire safety design around the world. Today the Fire Research Division at NIST continues to improve the body of knowledge regarding fire sprinklers with the mission of reducing loss of life and property due to fire.

David Evans received the Bronze Medal Award of the Department of Commerce in 1990 for his work on sprinkler response prediction.

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11.13 BURNING OIL SPILLS

One of the risks of oil drilling and transportation is that accidents can occur releasing natural crude oil or its refined products as oil spills. Oil contamination of land or water is an environmental hazard to life. Historically oil spill response has been limited to various mechanical means of recovering the spilled oil from land or water and then disposing or reprocessing the waste. Generally using mechanical recovery large amounts of oil contaminated materials need to be removed and treated. Mechanical recovery of oil in areas such as rocky shorelines, marshlands, and in ice laden waterways is impractical. In the 1980s burning oil in place - in-situ burning - - was explored as a primary technology for oil spill response.

The 1989 oil spill from the Exxon Valdez tanker onto the waters of Prince Williams Sound in Alaska focused national attention on oil spills. An estimated 42 million liters of oil were released from the ship into the water. Some of the oil, driven by winds and currents, was deposited on the shoreline of Prince Williams Sound. At the time of that spill, NIST and others were already engaged in the evaluation of burning as a response to oil spills. Industry was beginning to produce fire resistant booms that could be used to confine oil spilled on water to burn it in-place. It is a little known fact that using a fire resistant boom, approximately 57,000 liters of oil from the Exxon Valdez that had been in the water for nearly two days was confined and burned. The resulting fire lasting approximately 45 minutes consumed all but 1,100 liters of residue that remained in the boom [1].

Burning oil spills in-place normally produces a visible smoke plume containing soot and other combustion products produced in the burning. Lack of knowledge about the extent of the area affected by the smoke plume produced by burning crude oil spills and the possibility of undesirable combustion products carried in the plume have led to public concerns over the effects of intentional burning large crude oil spills. Unresolved questions about personnel and equipment safety from the heat and thermal radiation produced by large fires also has hampered application of burning to oil spills. In the decision process for approval of intentional burning of oil spills, local authorities need to have tools to quantify the likely benefits of the burning in terms of oil removal and the likely consequences in terms of the fire generated smoke plume. BFRL's in-situ oil spill research program was designed to develop quantitative information and software tools to aid authorities in making informed decisions. The lack of this information was an impediment to the acceptance and use of this emerging technology.

To understand and quantify the important features of in-situ burning it was necessary for BFRL to perform three scales of experiments. Laboratory tests furnished property data, experiments utilizing large-scale outdoor burn facilities provided mesoscale data and means to develop and evaluate instrumentation, and finally, actual burns of spilled oil at sea provided data on in situ burning at the anticipated scale of actual response operations [2]. In this research program, there has been continued interaction between findings from measurements on small fire experiments performed in the controlled laboratory environments of NIST and the National Research Institute of Fire and Disaster (NRIFD) in Mitaka, Tokyo, Japan, and large fire

Crude oil burn at the U.S. Coast Guard Safety and Fire Test Detachment mesoscale burn facility in Mobile, Alabama.

experiments at facilities like the USCG Fire Safety and Test Detachment in Mobile, Alabama where outdoor liquid fuel burns in large pans are possible.

Large scale burns of a confined oil layer up to 15.2 m x 15.2 m were used to determine a mean value for the burning rate per unit area of (0.052 +0.002) kg/s/m^2 and for the heat release rate per unit area is (2180 +100) kW/m^2 assuming a heat of combustion of 41.9 MJ/kg. The wind direction and speed in the outdoor burns contributed to the wide variation in fire extinction behavior observed although it did not appear to affect the average burning rate.

Crude oil released into a fire resistant containment boom and burned during the Newfoundland Offshore Burn Experiment conducted off the coast of St. John's Newfoundland on August 12, 1993.

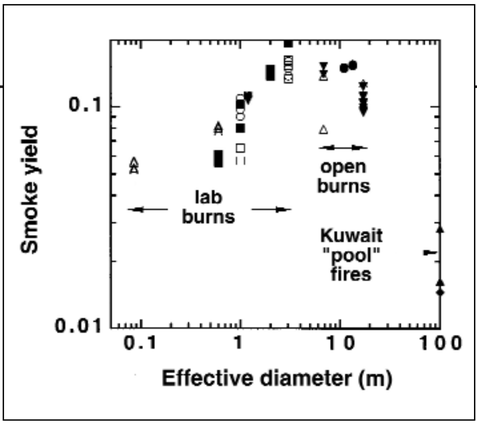
The amount of smoke particulate released from large oil fires is characterized by the smoke yield. Smoke yield is defined as the mass of smoke aerosol generated per mass of fuel consumed. The smoke aerosol collected during these experiments contained both solid material (graphitic carbon) and condensable hydrocarbons from the fire plume. Two methods for determining smoke yield were used in this study. The first was the flux method, which measured the smoke collected on a filter and the mass loss from the burning specimen [3, 4]. This type of measurement worked well in a laboratory test environment where all the products of combustion were collected and drawn through an exhaust stack.

The second method of determining the smoke yield is referred to the carbon balance method [4, 5]. This method required a determination of the ratio of the smoke mass in a given volume to the total mass of carbon in the form of gas or particulate in the same volume. This was accomplished by dividing the smoke mass collected on a filter to the sum of the smoke mass and the mass of carbon contained in the forms of CO and CO_2.

In the figure the smoke yield is plotted versus pool diameter. The effective diameter of the 2.7 m square pan was defined as the diameter of a circle (3.05 m) with area equal to the square pan. This figure includes other crude oil fires with "pan sizes" ranging from 0.085 m to 100 m [6 - 12]. The data from 2 m to 15 m based on five studies [6 - 10] with five types of crude oils (Murban, Arabian light, Louisiana crude, Murban-Arabian light mixture, and Newfoundland crude) appear to be independent of size; with one exception the data fall in the range 0.13 to 0.16. For the pan sizes larger than 3 m, the burns were performed outside where the ambient wind may affect the smoke yield. The results from two series of tests at 17.2 m are significantly lower than the results from 2 m to 15 m. The results from one series [6] range from 0.101 to 0.111 with a mean of 0.107 while the other was a single test with a value of 0.127 [10]. The cause for an apparent decrease is not known.

As an aid to effectively transfer the result of the BFRL research useful to authorities and emergency responders (decision makers about applying intentional burning of an oil spill) BFRL developed software to estimate the extent and concentrations of particulate in the smoke plume and at ground level.

The ALOFT (A Large Outdoor Fire plume Trajectory) model developed by



The effect of pool diameter on the smoke yield from burning different crude oils in laboratory and outdoor burns.

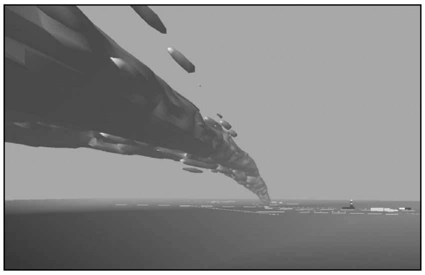
BFRL takes an approach similar to that of Ghoniem et al [13], but it uses finite-difference methods to determine the large scale mixing, combined with a Lagrangian description of the transport of the smoke and other pollutants. The ALOFT model differs from most of the atmospheric dispersion models in use today because it is a deterministic rather than an empirical model. The approach is to solve the equations governing the flow rather than to rely on empirical formulae that approximate the extent of the dispersion. Empirical models typically assume the pollutant is Gaussian-distributed in the plane perpendicular to the direction of the prevailing wind. The parameters defining the distribution are estimated from experiments. However, Gaussian models are inappropriate for two reasons: (1) the characteristics of the "source" are different from the smokestacks that are usually assumed by such models, and (2) the size of the source is well beyond those considered in industrial applications and thus outside of the experimental parameter range used to calibrate the models.

Aerial photograph taken of the second ACS burn, Prudhoe Bay, September 1994

During development ALOFT-FT predictions were compared with measurements taken at three field experiments. It should be pointed out that the experimental data were used to assess the accuracy of the model predictions. The data were not used to calibrate the model. This is an important distinction, and it points out the difference between a deterministic and an empirical model.

In early September 1994, Alaska Clean Seas (ACS) conducted at its Fire Training Ground in Prudhoe Bay, Alaska, three mesoscale burns to determine the feasibility of burning emulsified oil [14]. The photo shows an aerial view of the second burn. Twelve real-time aerosol monitors (RAMs), supplied by the US Environmental Protection Agency, the EPA's Emergency Response Team (EPA/ERT), were set out on meter high tripods, spread out in rows of three or four, at distances ranging from 1 km to 5 km downwind of the burn site to provide data on particulate concentrations at ground level. Model predictions showed good agreement with ground particulate concentration measurements. Simulations of the smoke plume from the burns showed good agreement with the observed plume trajectory (see photo).

To facilitate the approval of in situ burning as an oil spill response method, the Alaska Department of



Downwind view of the simulated smoke plume from the second ACS emulsion burn, Prudhoe Bay, September 1994.

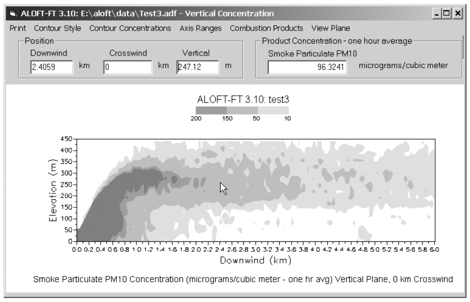
Environmental Conservation sought assistance from BFRL to use the newly developed ALOFT model for smoke plume trajectory to help develop guidelines for approval of intentional burning of spills. Two in situ burning scenarios were developed by NIST: one representing the burning of Cook Inlet crude oil in the Cook Inlet region and the other North Slope crude oil in the North Slope region.

In 1994, the State of Alaska used the results of this BFRL research as a basis for revision to their guidelines for approval of in-situ burning [15]. In the state guidelines BFRL's research is cited as:

Based upon the finding of the NIST report, "SmokePlume Trajectory from In-Situ Burning of Crude Oil in Alaska," the ARRT [Alaska Regional Response Team] has set a worse case, conservative downwind distance of 10 kilometers or approximately 6 miles as the primary value for "a safe distance" to conduct burning operations away from the human population... This distance may be modified (decreased or increased) after evaluating spill specific data such as location of spill, type of oil, and stability class of current meteorological conditions. If the burn involves either Cook Inlet or North Slope Crude and is located on the North Slope or in South Central Alaska, i.e., Cook Inlet/Prince William Sound, values from Table 7 [Burn Scenarios] of the NIST report, which presents a summary of smoke trajectory runs, may be utilized with a safety factor of 2X. Table 7 is included as an attachment to this review checklist.

To put the capabilities of performing smoke trajectory calculations in the hands of responders for the purpose of assessing the acceptability of initiating in-situ burning considering specific conditions at a site, BFRL developed the ALOFT-FT smoke plume trajectory software for personal computers [16,17]. This software produces trajectory predictions and downwind particulate concentrations within the uncertainty of the computations performed with more powerful computers at BFRL, but is capable of being run on portable computers in the field. A user-friendly interface was developed to allow users to input available data from site measurements or simply observations so that the calculation could be as specific to the incident as possible. Responders found the graphic output (see figure) provided by the model useful in explaining the findings of the calculations to local authorities for approval for intentional burning. Results from the ALOFT-FT model were used by local officials in the decision to intentionally burn fuel onboard the freighter, New Carissa grounded in Coos Bay, Oregon in February 1999. Burning was the only response option feasible to reduce the potential for a disastrous oil spill from the imminent breakup of the ship. The ALOFT-FT model was cited by the on-scene scientific advisors as providing the timely and critical information about the impact of burning on air quality.

Equally important to the quality of the computations was the quality and clarity of the graphic presentation of the results. The ALOFT-FT software provided information on the smoke plume trajectory and downwind concentrations in a manner that could be easily understood by local officials and public interest groups involved with the incident. The combined visual presentation of technical results provided by ALOFT-FT, the long history of verification testing, and the reputation of NIST as a source of high quality measurement and prediction technology provided the confidence for approval of intentional burning. This incident is the first time that intentional burning received wide spread publicity in the United States as a spill mitigation technique. Removing oil from the ship by burning helped to prevent millions of dollars of shoreline clean-up costs that would have occurred as the grounded vessel, battered by waves ruptured and split into two pieces shortly after the burns.



Example output screen from the NIST ALOFT-FT personal computer software used to quantify down wind particulate concentrations from large fires.

NIST measurement and prediction efforts have played a major role in establishing in-situ burning as an oil spill response method for use in the United States to minimize the pollution from oil spills. The better understanding of oil spill burning and the consequences produced by the NIST research enabled guidelines to be established whereby in situ burning is now considered to be a primary oil spill response technology. Burning is no longer regarded as an oil spill response method of last resort. Important data has been generated to quantify the smoke particulate in large fire plumes. Methods have been developed to reliably predict the downwind concentrations of particulate transported by wind blown fire plumes. Tools have been developed to make this information accessible and usable by the fire and oil spill response communities.

William (Doug) Walton received the Bronze Medal Award of the Department of Commerce in 1993 for leadership of field tests of burning of oil spills. David Evans received the Silver Medal Award of the Department of Commerce in 1995 for his leadership of experimental and analytical studies of burning of oil spills and of implementation of the techniques with state and federal environmental regulatory agencies.

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11.14 ZONE FIRE MODELING

The origin of zone fire modeling using computers dates back to 1976 with the publications and talks given by Quintiere [1], Reeves and MacArthur [2], Mitler [3], and Pape and Waterman [4]. Of these early models, only Harvard 3 developed by Emmons, Mitler, and Trefethen [5] survives today as a substantially revised model, FIRST [6]. These early computer models ran on mainframe computers: an inconvenient format to distribute to the fire community. Other early models developed at NIST include: ASET by Cooper and Stroup [7], DETACT by Evans and Stroup, and later the multiroom models by Tanaka [8], Harvard VI by Emmons and Mitler [9], and FAST by Jones [10].

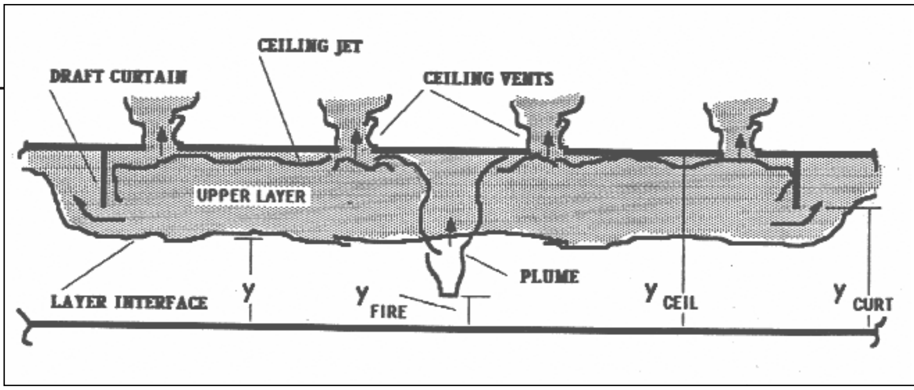
When the IBM PC was developed, Walton recognized that NIST's fire programs could be moved from the mainframe computers to the PC and made available to the fire protection engineering community. Walton simplified ASET and rewrote it to run on a PC. The new program, ASETB [11], became one of the most widely used fire programs ever released by NIST. DETACT was converted to DETACT-QS by Walton and Stroup [12] and DETACT-T2 [13] by Evans and Stroup. Both programs would run on a PC. These programs are used today and are part of NFPA 204, 2002.

Walton started a computer bulletin board for the NIST computer programs and modified most of the existing mainframe programs such that they could run on the PC. He provided documentation for each program and a description on how to use the program. This effort made available NIST's fire programs to the fire protection community. Stroup and Davis converted Harvard 5 to run on a PC. The new program was renamed FIRST. At the time, it was the most complete fire model from a fire physics standpoint and was the first zone model to provide a self-consistent model of the fire.

Gross and Davis used FIRST to model STARK, the USS Stark (FFG 31) 1987 shipboard fire caused by an Iraqi Exocet missile striking the frigate. FIRST was used because other NIST fire models did not have adequate fire physics to give realistic answers. During this project, Davis rebuilt the solvers in FIRST, developed addition fire physics, and released the second version of FIRST [14].

Fire modeling at NIST in the middle to late eighties continued development of the multiroom zone models HARVARD 6 by Rockett and Mitler [9] and FAST by Jones [10], the introduction of a new multiroom zone model CCFM by Forney and Cooper [15], and. the development of a single room fire model LAVENT (Link Activated Vent) by Davis [16] based mainly on a theory developed by Cooper [17]. LAVENT featured new physics that included the activation of fusible links by a ceiling jet that was modified by the presence of a hot layer. The impact of the position of the detector both below the ceiling and radially away from the fire could be predicted. This new algorithm represented an upgrade in sophistication from the program DETACT-QS. LAVENT could be used to estimate the impact of ceiling venting on the upper layer and on detector activation that represented a substantial advancement in zone modeling. Davis wrote a graphics display program, GRAPH, using a NIST developed, Fortran callable graphics package [18] to display the output of LAVENT. LAVENT is in use today and featured in NFPA 204, 2002.

With the increasing fiscal constraints of the early nineties, it was decided that only one multi-room zone model should be developed. Forney and Jones merged FAST [10] and CCFM [15], taking the best from each, to produce CFAST [19]. An upgrade occurred for CFAST as Forney, Peacock, and Reneke changed the model structure, solver and added new fire physics. Later, Forney added a sophisticated radiation package and a corridor algo-



An example of a fire scenario that demonstrates much of the fire physics included in LAVENT.

rithm. Today, CFAST is one of the leading multi-room zone models and is used worldwide.

FPETool was being developed in the early nineties by Nelson and Deal [20]. The model was based on the ASETB zone model and included a number of algebraic algorithms to provide a toolbox for the fire protection engineer. This model became one of the most widely used models of the nineties.

In the middle nineties, Gott of the Naval Facilities Engineering Command and Notarianni of NIST devised an experimental program to examine fire detection in military hangars [21]. Davis was brought into the program to model the experiments as preplanning for instrument placement and fire sizes. Davis used the computer models LAVENT and Harwell FLOW3D [22] to examine instrumentation and fire sizes for the two hangars that were located in Hawaii and Iceland. Gott and Notarianni, working with major industrial partners, allowed BFRL to test a number of different heat detectors, smoke detectors, UV/IR detectors and slow and fast actuating sprinkler links. Notarianni and Davis designed the experimental fires such that threshold effects for detector activation could be studied. These experiments were unique due to the variety of devices tested, the threshold effects for detectors demonstrated in the experiments, the extensive use of scientific monitoring devices to clarify the detector behavior, and the quality of the experiments that provided a basis for further model development.

In analyzing the Navy hangar experiments, it was evident that none of the zone fire models could perform an adequate job predicting the plume centerline temperatures or the ceiling jet temperatures reached by the largest fires. Davis developed a method to model these experiments using a substitute source theory for plume temperatures developed by Evans [23] and a variable radiation fraction as a function of fire size based on experiments by Yang et. al. [24]. The resulting algorithm represented a substantial step forward in modeling fire phenomena when a hot layer was present. Davis used the Navy data to develop a new

Fire test, in a Navy aircraft hanger, Keflavik, Iceland, to determine how the latest generation of fire detectors and sprinkler heads respond to increasing sizes of fires. Many of the team members shown in the photograph are from NIST, other organizations that made hangar experiments possible include: members from The Naval Facilities Engineering Command, The Naval Air Stations at Keflavik, Iceland and at Barbers Point, Hawaii, The U. S. Air Force, the U. S. Marine Corps, The U. S. Army Corps of engineers, Simplex Time Recorder Co., The Viking Corporation, Detector Electronics Corporation, Detection Systems, Inc., and Alison Control, Inc.

ceiling jet model and packaged the new fire physics in a zone model, JET [25] that used many of the older algorithms of LAVENT. JET was the first of the zone models to use Microsoft Visual Basic to build a user input module.

The Navy data also proved useful in demonstrating that CFAST was predicting too high of temperatures. The earlier data sets that were used for FAST and CFAST did not have the instrumentation to demonstrate this problem convincingly. Paul Reneke found and corrected the error.

The Navy hangar data has been used as an aid in the design of fire protection for high ceiling structures worldwide. Based on the information collected in the project, fire protection design was substantially changed in military hangars. It ranks high in NIST fire experiments that impacted fire protection engineering.

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